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THE EFFECTS OF URBAN EXPANSION ON TEMPERATURES IN THE CITY OF EDMONTON, ALBERTA

BY

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled The Effects of Urban Expansion on Temperatures in the City of Edmonton, Alberta, submitted by Malcolm Owen Berry in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

An estimation of changes in air temperature within the city, resulting from urban expansion, is obtained for Edmonton. This is achieved by means of a comparison between Edmonton temperatures and temperatures at Wetaskiwin, a small community 40 miles south of the city. The comparison is based on daily maximum and minimum temperature data which were available for a period of about 36 years.

The substantial differences in latitude and elevation between the two stations require that caution must be used in attributing temperature differences to urban effects. In order to minimize the possible influences of factors unrelated to urban climate, the average temperature differences between Edmonton and Wetaskiwin are computed for two periods--1931 to 1940 and 1956 to 1965. Changes in the differences from the earlier to the later period are then computed, for both maximum and minimum temperatures. These changes coincided with a population increase of 215,000, from an initial level of 85,000.

For minimum temperatures, a substantial increase of 2.2°F in the Edmonton-Wetaskiwin temperature difference is found. It is shown that this increase probably gives a good estimate of the change in city temperature that resulted from urban expansion. In cold weather (temperatures below 0°F), the amount of the increase is found to be largest. It is also found to be inversely proportional to temperature in cold weather. This dependence on temperature probably indicates that space heating was a major determinant. In warmer weather, the increase in city temperature is found to be smaller (less than 2.0°F). It is shown

that city-country differences in radiation rates and release of heat stored in the urban fabric were probably determining factors in this case.

To an extent, Edmonton-Wetaskiwin differences for maximum temperatures are found to be inversely proportional to maximum temperatures. Consequently, caution must be exercised in interpreting changes in these differences as having resulted from urban expansion. The average increase in city maximum temperatures computed from the change in differences is found to be 0.7°F, or about one third that for minimum values.

On a seasonal basis, the increase in maximum temperatures is found to be least in spring, and greatest in early winter. The seasonal trend in daytime lapse rates and wind speeds indicates maximum dispersion rates in spring, with a minimum in early winter. Consequently, it is postulated that these factors may have been dominant in determining the amount of increase in maximum temperatures.

The city temperature data used are for the airport, which is located some distance from the center of the urban area. It is difficult to determine how representative these data are of other parts of the city.

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INTRODUCTION

Since the middle of the 19th century there has been a rapid increase in both the size and the number of cities. As a result of this shift in population from rural to urban areas, the large city is becoming the typical home of mankind. Urbanization has made the influence of the city on man and his environment a matter of major importance. It is the intent of this thesis to investigate one aspect of this urban development--its effect upon air temperatures within the city.

A number of studies have been conducted in an attempt to measure the effects of urbanization on temperature. For the most part these studies fall into two categories: the comparison of city temperatures with those at an adjacent rural station for a specific time period (commonly 5 or 10 years), and the detailed study of city temperature patterns based on data collected by means of some type of mobile recording equipment. This latter approach generally involves measurement of temperatures at a larger number of points in the city, within a short period (typically 1 or 2 hours), by means of some type of thermometer attached to a motor vehicle. The recorded data are then used to construct isotherms which represent what is effectively the horizontal distribution of temperature in the city at an instant of time.

Both these methods have serious shortcomings. The comparison of temperatures between urban and rural sites for a specific period gives some measure of urban influences; however, topographical or other non-urban factors may influence the data. The study of urban temperature

structure by use of mobile recording devices provides quite detailed data. Unfortunately, the amount of work involved in measuring temperatures throughout the city generally limits the number of situations that can be studied. Consequently, it is not usually possible to make generalizations about city temperature from the limited number of cases available.

There is one approach to the problem of city temperature which avoids some of the difficulties inherent in the two methods discussed above. This approach involves the comparison of city temperatures with those at a rural site. However, instead of computation of mean city-country temperature differences for a single period, mean differences are computed for two periods between which there is considerable change in the size of the city. The change in the mean differences from the earlier to the later period is then computed. By use of this method, the influence of non-urban factors such as topography should be minimized, because their effects will tend to be much the same in both periods. Consequently, the computed changes in difference should more accurately reflect urban growth.

This approach is not without limitations. Because it is not usually possible to obtain temperature data in suitable form for an early period in which the city was very small, the computed change in city-country temperature differences must normally represent the expansion of the city beyond an initial period in which the population was sufficiently large to have already substantially influenced city temperatures. In other words, the computed changes in city temperatures represent a change from one level of urbanization to another, and consequently may not give a true picture of urban-rural differences.

This method of two-period comparison of temperature differences is best suited for use for a city where there has been a relatively large change in city-country temperature differences over a fairly short period of time. This normally implies two conditions--an environment in which urban effects produce substantial city-country temperature differences, and a rapid expansion of the city itself. Edmonton meets both of these requirements. Since the 1940s, it has been one of North America's fastest growing cities. The low temperatures prevalent in the city for much of the year require high levels of space heating. Heat from this source can be a major cause of city temperature excess, relative to the surrounding countryside. Additionally, these low temperatures are often associated with stable atmospheric conditions and light winds. This combination tends to minimize the dispersion of urban effects.

The estimation of the amount of temperature change in the city resulting from urban effects is of limited value unless some explanation of the cause of these changes can be given. The lack of an adequate theoretical assessment of urban climate makes this explanation difficult. Nonetheless, in addition to the computation of the changes in Edmonton's temperature, an attempt is made, within the limits of the data available, to relate these changes to such factors as stability and wind. Additionally, the difficulties and limitations involved in using city-country temperature differences as an estimate of urban influences are discussed in some detail.

A review of the literature indicates that computed values of city-country temperature difference vary considerably from one location to another. There is generally little explanation given for these discrepancies. These differences probably arise partially from differ-

ences in climate and topography. Consequently, for this study of Edmonton, considerable effort is made to describe the local topography, and to give a detailed description of the climate, relative to the climate of some other major cities.

CHAPTER I

INTRODUCTORY REMARKS ON URBAN CLIMATE

General

The climate over small areas of the earth's surface (microclimate) is the product of a delicate balance among numerous factors, both in the air and on the ground. The smallest changes in the local environment can, therefore, significantly alter the associated microclimate. The establishment and growth of urban areas result in a multitude of often drastic environmental changes. The changes are not only those of a relatively permanent nature, such as the addition of buildings and roads, but also include those of a more fluid nature involving a multitude of human activities. In terms of climate, the city is not really an entity, but a composite of the innumerable microclimates associated with its highly irregular form. In addition to varying with the large-scale weather patterns, these small-scale climates are also influenced by the continually changing nature of the city and the human activities within it. The term "city climate," therefore, implies an average value, and this average, or whole, will not, in many circumstances, adequately represent many of its parts. When data are available from only a limited number of points within the urban area, such as is often the case with temperature, care must always be taken to ascertain the representativeness of the values. In many cases, data collected at a point may strongly reflect unique influences found only in the immediate area.

The rural climate to which the city is usually compared is also a

composite of many individual microclimates. Although these small-scale climates usually tend to be more homogeneous than in the case of the city, variations in such things as soil, vegetation, and topography can often play an important role in influencing the local weather.

In spite of the many variations within and between cities, it is possible to enumerate a number of factors which, to a greater or lesser extent, serve to distinguish most urban climates from their rural counterparts. In the remainder of this chapter an attempt will be made to outline the more important of these.

Air Pollution

Air over the city often contains large quantities of contaminants. This air pollution consists of both particulate and gaseous matter. Excluding water vapour, which is not usually considered as pollution, it is the particulate matter associated with pollution that, for the most part, affects the transmission of radiant energy through the atmosphere. This particulate matter is not a unique by-product of human activity--much of it results from natural causes, especially the entrainment of dust from the earth's surface. Nonetheless, cities normally produce substantial quantities of particulate matter, with industry, space heating, power production, incineration, and motor vehicles acting as the major sources. In cities located at low latitudes, where insolation is particularly intense, atmospheric photochemical reactions involving hydrocarbons and oxygen act as another major source of particulate matter. Compounds required for these reactions are produced primarily by internal combustion engines and the petroleum industry.

Some idea of the effects of urban development on particulate concentrations can be gained from data provided by the U.S. Department of Health, Education and Welfare (1961), which has tabulated mean values for cities

of varying sizes, as shown in Table I-1.

TABLE I-1 - SUMMARY OF NASN[a] SUSPENDED PARTICULATE SAMPLES FOR URBAN STATIONS BY POPULATION CLASS, 1957-63. SOURCE: U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE (1961), AND SUPPLEMENTS FOR 1962 AND FOR 1963

Population class	No. of Samples	No. of Stations	Mean ($\mu gm/m^3$)
1. 3×10^6	316	2	182
2. $1 \times 10^6 - 3 \times 10^6$	516	3	161
3. $0.7 \times 10^6 - 1 \times 10^6$	1191	7	129
4. $0.4 \times 10^6 - 0.7 \times 10^6$	3053	19	128
5. $0.1 \times 10^6 - 0.4 \times 10^6$	9531	92	113
6. $5 \times 10^4 - 10 \times 10^4$	5806	81	111
7. $2.5 \times 10^4 - 5 \times 10^4$	1606	23	85
8. $1 \times 10^4 - 2.5 \times 10^4$	484	6	80
9. $< 10^4$	150	5	100
10. rural	...	..	30

[a]National Air Sampling Network

Stations participating were members of the National Air Sampling Network. The anomalously high value for small communities is somewhat difficult to explain. Although, according to these figures, large cities have mean concentrations as much as sixfold higher than rural (background) values, it is of interest to note that expansion of a city from 50,000 to 400,000 people produces an average pollutant increase of only 20 per cent. It must be borne in mind, however, that there will be considerable variations in these values from city to city, as a result of differences in sources and climate.

The interaction of the constituents of the atmosphere, including pollution, with the radiant energy traversing it is extremely complex.

Although analysis of the total problem is currently rather incomplete, some useful statements can be made. At this point we are concerned primarily with the effects of the urban pollutant veil on incoming solar radiation. A number of studies indicate that, over large cities, insolation is generally reduced by about 10 to 30 per cent by this veil, which acts to scatter and absorb incident radiation. In addition to its dependence on particulate concentration, the amount of attenuation will be influenced by the size of the particles and the angle of the sun (which determines the length of path). Table I-2, after Steinhauser (1934), gives mean values of the reduction of total radiation received at the surface in the city, as a function of season and angle of the sun for Vienna, Leipzig, and Frankfurt.

TABLE I-2 - PERCENTAGE LOSS OF INCOMING RADIATION IN CITY AIR AS COMPARED TO COUNTRY AIR. SOURCE: STEINHAUSER (1934)

	Solar elevation angle (degrees)			
	10	20	30	45
Winter	36	26	21	..
Spring	29	20	15	11
Summer	29	21	18	14
Fall	34	23	19	16

Table I-3 gives similar data from Emslie (1964) for Toronto. Both sets of measurements indicate maximum attenuation in winter, with the minimum in spring. This seasonal variation corresponds to the seasonal variation in pollution concentrations. The fact that Emslie's values were higher on Wednesday than on Sunday presumably indicates the importance

TABLE I-3 - PERCENTAGE LOSS OF SOLAR RADIATION IN TORONTO IN COMPARISON WITH A SUBURBAN STATION SOURCE: EMSLIE (1964)

	Wednesday	Sunday
Winter	11.4	3.4
Spring	3.1	5.3
Summer	7.4	5.7
Fall	4.3	4.1
Annual	6.6	4.6

of industry and perhaps motor vehicles as pollution sources in the city, especially in winter. It is not readily apparent why the Toronto figures are so much smaller than those for the European cities. It is conceivable that the station used by Emslie for comparative purposes (9 miles east of the city center) was not at a sufficient distance to be free of urban influences.

Fog

The large number of condensation nuclei, combined with the moisture release associated with some types of combustion, tends to increase the frequency of fog occurrence over the city, serving to reduce further the solar energy reaching the ground. For Edmonton (population 160,000 at the time) Robertson (1955) found that the release of water vapour from combustion of natural gas could, in very cold weather, reach values as high as 5,000 tons per day. He suggested that the high frequency of occurrence of dense (visibility less than five eighths of a mile) winter fog in the city--64 hours per winter as compared with 33 hours in a nearby small community--was related, at least in part, to this moisture release. For Paris, Maurin (1947) gave a city-country comparison of the number of days with fog reducing visibility to less than 1 mile, as shown in Table I-4.

TABLE I-4 - FOG DAYS FOR PARIS.
SOURCE: MAURIN (1947)

	Winter	Summer
City	350	49
Country	60	6

Values given are per 1,000 days. The substantial increase in the occurrence of fog in the city is apparent.

Albedo

Some compensation for the loss of solar energy over the city as a result of fog and pollution is probably provided by a decrease in albedo, although data on this point are scant. Kung, Bryson, and Lenschow (1964) have estimated that, in the absence of snow cover, cities cause a reduction of albedo of about 10 per cent. Since snow serves to reflect about 90 per cent of incident short-wave radiation, it seems probable that melting, snow removal, and the large number of snow-free vertical surfaces in the city would serve to reduce its albedo considerably relative to the surrounding countryside in winter months.

Artificial Heat

The artificial heat released in the city rarely has any counterpart in the rural environment. It is a result primarily of industrial activity and space heating. Power production and motor vehicles may also make significant contributions. Various estimates of the total artificial energy produced in different localities, relative to the amount received from solar radiation, have been tabulated by Kratzer (1956), and are given in Table I-5. These figures indicate that artificial sources make a sub-

TABLE I-5 - RATIO OF ARTIFICIAL ENERGY TO SOLAR ENERGY FOR VARIOUS CITIES
SOURCE: KRATZER (1956)

Vienna	1/4 - 1/6
Berlin	1/3
Sheffield	1/5

stantial contribution to the total energy supply. However, it must be born in mind that urban heat is highly subject to ventilation effects. For example, Mindling (1911) estimated that the air over a city as large as New York is changed, on the average, twenty-four times per day. This led him to suggest that figures such as those in Table I-5 should be divided, roughly speaking, by twenty-four.

Generalizations about artificial heating in cities are difficult to make because of major differences from one city to another. For example, the relative importance of space heating compared to industrial heat supply varies markedly, depending on such things as the coldness of the climate and the nature and location of industrial development.

Atmospheric Mixing

Having considered energy input to the urban environment, let us now examine the ways by which excess energy is dissipated. Putting aside radiation effects for the time being, the major process by which energy loss occurs is atmospheric mixing with the surrounding environment. Dilution of atmospheric pollutants is also brought about primarily by this mixing process.

Since molecular diffusion is a relatively insignificant factor under most meteorological conditions, mixing is due primarily to turbulence (eddies). The turbulent energy available may be classified either as

mechanical or thermal. The former is produced primarily by wind shear, the latter by buoyancy forces which often arise from temperature differences between the ground and the air above. In the context of the interaction between wind and the earth's surface, mechanical turbulence is proportional to wind speed and surface roughness. Above the surface, mechanical turbulence increases with increasing vertical gradients of wind velocity.

Thermal turbulence is associated with convection, which normally results from air being cooler than the underlying surface. This relative warmness of the surface is usually a result of extensive heating by sunlight or advection of cooler air over warmer surfaces. Heat released by urban areas can also play a part.

Strong low-level winds will always cause some turbulence, and hence mixing, regardless of stability. Persistently strong winds can gradually weaken or destroy an inversion by means of this mixing process, which tends to create uniformity in the vertical. The low-level wind flow is dependent, however, to a considerable extent on the flow at higher levels for its energy. Since downward momentum transfer will decrease with increasing stability, light surface winds are normally associated with highly stable conditions. On the other hand, unstable conditions facilitate vertical momentum transfer and hence tend to increase surface wind, although this is balanced to some extent by the fact that markedly unstable conditions are often associated with weak winds aloft. This coupling of upper and lower winds through momentum transfer will normally tend to reduce the winds at higher levels.

In general then, stable conditions, and the relatively light winds often associated with them, tend to minimize mixing between the urban area and its surroundings, while stronger winds and less stable conditions

act in an opposite manner. A quantitative assessment of this mixing process is easiest to obtain through consideration of pollutant concentrations, because these are more readily measured than heat and momentum fluxes. Table I-6, after Ginner and Hess (1937), gives nuclei count as a function of wind speed for city conditions.[1] The rapid increase in mixing as wind speed increased is apparent.

TABLE I-6 - CITY NUCLEI COUNTS AT DIFFERENT WIND SPEEDS.
SOURCE: GINNER AND HESS (1937)

	Wind Speed (m/s)						
	0	1	2	3	4	5	>5
Summer	18300	17400	15300	11300	4700	3200	1600
Winter	32400	29000	26600	20100	13400	8100	....

A relatively small wind speed of 4 m/s reduced concentrations to less than half the value for calm conditions.

The increased surface roughness of the city also serves to convert an increased amount of the energy of the flow into turbulent energy. Consequently, the decrease of city wind--commonly 10 to 20 per cent--resulting from this surface roughness, does not necessarily indicate reduced ventilation. Any reduction in wind flow may also be compensated at times by increased instability over the city. This instability is a product of increased city heat, and serves to increase wind speeds by

[1]Since the original paper was not available, these figures were obtained from Kratzer (1956) who failed to specify what city (or cities) the data represent.

enhancing downward momentum transfer from the winds aloft, as previously discussed.

Long-Wave Radiation

Long-wave radiation is a major sink of energy, both in the city and the country. As this radiation traverses the atmosphere, it is attenuated primarily by water vapour, carbon dioxide, and particulate matter. For the 3 to 30 micron range in which most of this radiation is emitted, there is a major "window" in the water vapour-carbon dioxide absorption spectrum between 8 and 12 microns. This "window" coincides with the region of maximum emission, and it is here that the city can serve to reduce net emission by virtue of its increased pollutant concentrations. There is a dearth of quantitative assessments of this reduction. Robinson (1947, 1950) has estimated for London (Kew Observatory) an average decrease in long-wave radiation of about 10 per cent compared to the surrounding country for nights with visibilities greater than 1,500 meters.

There appears often in the literature the suggestion that radiation between buildings and other irregular features of the city may serve to reduce the net upward flux of radiation. Apparently there is no concrete evidence to support or repudiate this theory. The increased amounts of fog generally associated with cities will also act to reduce outgoing radiation under some conditions.

Rain may serve to reduce attenuation of long-wave radiation by reducing the concentration of larger-sized particles in the city air. As rain droplets fall they accumulate particles whose sizes, according to Haagen-Smit and Wayne (1968), exceed 2 microns in diameter. Again, there is little quantitative assessment of this effect. Smith (1964) has, however, computed from a rather idealized model that a rainfall of 0.2 inches per hour would decrease, in less than 2 hours, large particle concentration

to about one third its initial value.

Latent Heat Effects

The combination of extensive waterproof areas and large scale drainage systems in the city expedites removal of surface moisture. The resulting reduction of evaporation frees energy for other processes such as heating. On the other hand, additional moisture is added to the urban environment as a result of various human activities. The watering of lawns, the washing of streets, and various industrial processes are examples. It is not clear whether the net effect of these various factors is to increase or reduce the amount of available energy converted into latent heat. Additionally, the formation and dissipation of the excess amounts of fog over the city can act as a source or sink of sensible heat in some instances.

Storage

The extensive use of such materials as stone, brick, and concrete gives the city a higher heat capacity than the surrounding countryside. This increased ability for heat storage is enhanced by an increased ability for downward conduction. Consequently, the city acts as a giant reservoir, tending initially to heat more slowly, then to cool more slowly later in the day as stored heat is released. Again, quantitative assessment of this effect is lacking.

CHAPTER II

CITY TEMPERATURE

Mean Temperature

Having considered various factors affecting the city's energy budget, let us now attempt to relate this information to the observed temperature differences between city and country. The large number of variables involved, combined with a serious lack of quantitative assessments, makes theory difficult to relate to observation; nonetheless, it is possible to make some generalizations.

From a variety of sources Kratzer (1956) has compiled a list of mean city-country temperature differences, reproduced in Table II-1.

TABLE II-1 - MEAN CITY-COUNTRY TEMPERATURE DIFFERENCES (D) FOR VARIOUS CITIES. SOURCE: KRATZER (1956)

City	Period	D (°C)	City	Period	D (°C)
Paris	1816-60	0.7	Milan	1921-24	1.3
Moscow	1901-10	0.7	Jersey City	1917-27	1.8
Nuremberg	1922-31	0.9	London	1810-12	0.8
Berlin	1881-1910	1.0	Washington	1920-24	0.6
Cologne	1912-31	0.8	Leningrad	1901-10	0.7

Table II-2 lists mean differences for cities of different sizes, after Landsberg (1956). Both sets of data indicate a net warming of about 0.6°C to 0.9°C on the average. This increase is probably a result primarily of artificial heat release within the urban area, and the reduction of heat loss by long-wave radiation due to pollution and interception by buildings.

Decreased albedo may also play a part.

TABLE II-2 - MEAN CITY-COUNTRY TEMPERATURE DIFFERENCES AS A FUNCTION OF CITY SIZE. SOURCE: LANDSBERG (1956)

No. of Cities	Population	Difference (°C)
10	over 1,000,000	.72
10	500,000 - 1,000,000	.61
10	100,000 - 500,000	.55

In terms of urban expansion, it is important to note that Table II-2 illustrates the fact that the major part of the city's temperature excess develops when its size is less than half a million people. Growth above this size, on the average, produces only modest increases in this excess. The reason for this is not well understood. Perhaps there is a threshold in size above which a centrally located observing station is insulated under most conditions from intrusions of relatively unmodified country air. In the city, the reduction of incoming solar radiation as a result of increased pollution and fog would cause, in the absence of other factors, a decrease in temperature. The fact that cities are generally warmer than the adjacent country indicates that other factors must more than compensate for this reduction.

The Diurnal Variation in City Temperature Excess

Before proceeding with a discussion of differences in terms of maximum and minimum temperatures, it is necessary to consider how representative these values are of the diurnal variation. Typical examples of this variation are given in Table II-3 for Bremen, after Mey (1933).

TABLE II-3 - DIURNAL VARIATION IN CITY-COUNTRY TEMPERATURE DIFFERENCE FOR BREMEN (°C). SOURCE: MEY (1933)

Local Time	2	4	6	8	10	12	14	16	18	20	22	24
January	.7	.5	.5	.5	.4	.2	.2	.6	.7	.8	.8	.7
June	2.4	2.4	1.2	.8	.1	0	-.4	0	.9	1.5	1.9	2.5

In winter, the maximum difference generally occurs in the evening, with a gradual decline in difference through the night. This decrease normally becomes more rapid after sunrise, with the minimum difference occurring in the afternoon. In summer, the maximum difference tends to occur later--around midnight. There is a small decrease in difference through the remainder of the night followed by an abrupt decrease after sunrise as the country warms more rapidly. As in the winter, minimum difference tends to occur in the first half of the afternoon. It is in this latter period that maximum temperatures are usually recorded. Consequently, city-country difference at maximum temperature time often represents the minimum in the diurnal variation of this difference. On the other hand, minimum temperatures, while often not occurring at the time of maximum difference, generally occur at a time when this difference is relatively high. The daytime minimum in the city's temperature excess probably results primarily from the fact that solar heating decreases stability and hence increases ventilation and mixing. Loss of heat to storage and by attenuation of incoming radiation may also be major factors.

Seasonal Variations in City-Country Temperature Differences

By comparing the annual march of city-country temperature difference to the seasonal variation in parameters which could affect this difference, it might seem possible to evaluate the relative importance of these

variables, and thus partially overcome the lack of theoretical assessments. In practice there are two major difficulties associated with this approach. First, the number of influential factors is substantial, and their nature varies considerably from one city to another. The second difficulty involves the actual temperature data. Most of the observations involve single-period comparisons between the city and an adjacent country station. In other words, mean temperature differences are computed for, say, a single ten-year period. Many of the differences found through this approach may have arisen from topographical or other factors unrelated to urban influences.

In spite of the above difficulties, it is still of value to consider seasonal variations. Table II-4 shows seasonal variations for four cities, the first two of which are somewhat typical. The other two indicate the anomalous results often obtained. Data are for Munich[1], London (Howard (1833)), Lyons (Piery (1946)), and Vienna (Francini and Lauscher (1952)).

For mean temperatures, the city excess tended to be maximum in fall, minimum in spring, in the typical cases of Munich and London. Lyons, on the other hand, had a maximum in spring, whereas Vienna showed little seasonal variation. For the two cases where data were subdivided into maximum and minimum values, it can be seen that the maximum temperature excess was greatest in December. For the minimum values the excess was greatest, roughly speaking, in the fall in the more typical Munich case. It should also be noted that, for a considerable portion of the year, Munich was cooler than the country at maximum temperature time. This is

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[1]The data for Munich come from Kratzer (1956), who omitted the original reference.

TABLE II-4 - SEASONAL VARIATION IN CITY-COUNTRY TEMPERATURE DIFFERENCE FOR VARIOUS CITIES (°F)

Month	J	F	M	A	M	J	J	A	S	O	N	D
Munich[a]												
Mean	1.8	2.0	1.6	1.4	1.6	1.4	1.8	2.0	2.1	1.8	1.4	1.8
Max.	0.0	0.1	-0.3	-0.3	-0.6	-0.1	-0.5	-1.6	-1.4	-0.5	0.3	0.7
Min.	3.7	3.7	3.5	3.9	4.1	3.0	3.4	4.2	4.0	3.9	2.8	2.8
London[b]												
Mean	2.0	1.3	1.3	0.8	0.5	1.2	1.0	1.2	2.2	2.0	2.2	1.7
Lyons[c]												
Mean	0.4	0.6	0.6	1.1	1.0	1.0	0.8	0.9	0.6	0.6	0.2	1.6
Max.	0.1	0.3	0.1	0.1	0.3	0.3	0.3	0.1	0.5	0.1	0.6	1.0
Min.	0.9	0.9	1.2	2.1	2.0	2.1	1.9	2.6	0.8	1.1	0.9	2.0
Vienna[d]												
Mean	0.5	0.7	0.7	1.0	0.7	0.7	0.7	0.8	0.7	0.7	0.7	0.7

[a] P. Albert Kratzer The Climate of Cities, trans. American Meteorological Society Translation Service. Air Force Cambridge Research Laboratories, Bedford, 1956, p. 69. (This is a secondary source--Kratzer omitted the original reference.)

[b] L. Howard, The Climate of London Deduced from Meteorological Observations Made in the Metropolis and at Various Places Around It. 3rd ed., n.n., London, 1833, p. 13, cited by Kratzer, op. cit., p. 69.

[c] M. Piery, Le Climat de Lyon et de la Region Lyonnaise. n.n., Lyon, 1946, p. 88, cited by Kratzer, op. cit., p. 70.

[d] O. Francini and F. Lauscher, "Neue Temperaturnormalwerte, für das Stadtgebiet und die Landschaft um Wien," Wetter und Leben, Vol. 4, 1952, pp. 1 ff., cited by Kratzer, op. cit., p. 70.

not an unique case--temperature excess in the city in the afternoon is by no means a universal effect. The typically small magnitudes of these maximum temperature differences require that extreme caution must be exercised in interpreting the differences as resulting from specific urban factors. Finally, it should be noted that, even though there is considerable variation from city to city in the data of Table II-4, these cities do not drastically differ from one another in climate.

Stability, Wind and City Temperature

Stable conditions over the city should tend to enhance its temperature excess by trapping artificially created heat and, in the case of minimum temperatures at least, by increasing pollutant concentrations. Unfortunately, specific data are limited. Some data relating city temperatures to wind are available, however. As previously discussed, wind is related to stability to some degree. Consequently, wind data give some measure of stability, with light winds implying more stable conditions. The relation between wind and city-country temperature difference for Paris, after Besson (1927), is shown in Table II-5. Only minimum temperatures were considered.

TABLE II-5 - DIFFERENCES IN MINIMUM TEMPERATURES (°C) IN RELATION TO CLOUDINESS AND WIND SPEED. SOURCE: BESSON (1927)

Mean Cloudiness	Wind Speed (m/s)				
	0.0-1.0	1.1-2.4	2.5-5.0	>5.0	All Winds
0.0 - 2.0	3.7	2.1	1.5	0.2	2.6
2.1 - 4.0	2.9	2.2	1.4	0.7	2.0
4.1 - 6.0	2.1	2.3	0.9	0.8	1.7
6.1 - 8.0	1.8	1.1	0.5	0.2	0.8
8.1 -10.0	1.0	0.8	0.8	0.1	0.8
0.0 -10.0	2.4	1.7	0.9	0.4	1.4

The rapid drop in city excess with increasing wind is apparent. It should be noted, however, that even with night winds as high as 3.8 m/s, there was still a substantial temperature difference. The effect of wind appeared to diminish with increasing cloudiness. Based on data from seven cities, Fuggle and Oke (1968) have constructed a graph to indicate critical wind speed for the effective elimination of the urban heat island. This graph, reproduced in Fig. II-1, also indicates the persistence of urban influences

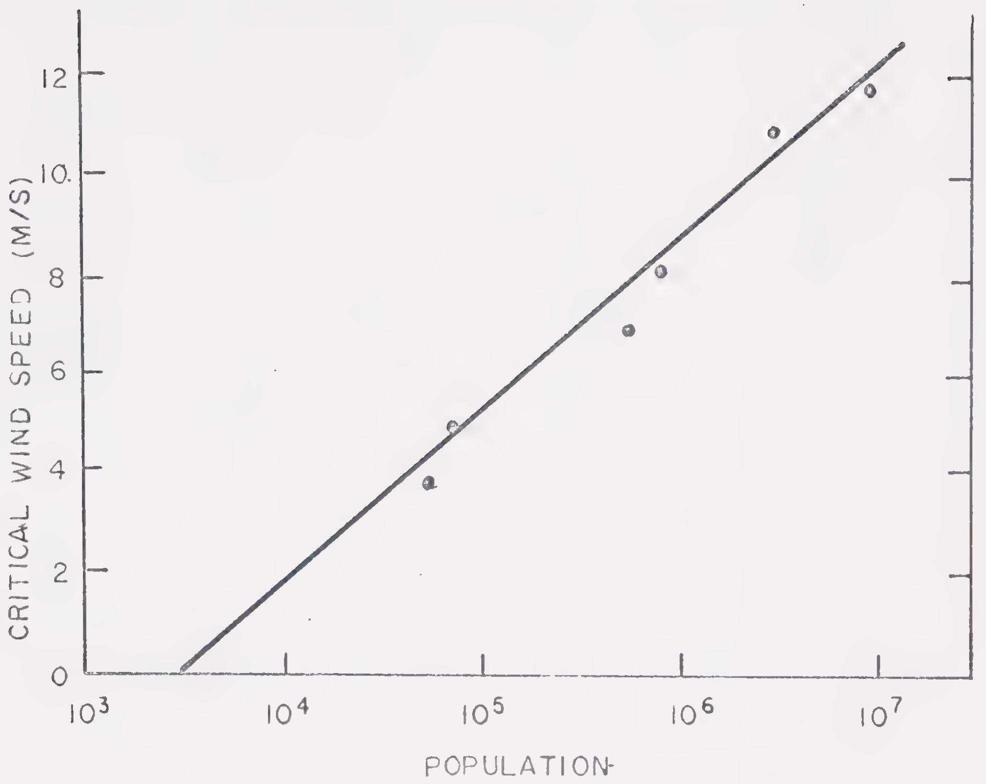

Fig. II-1. Critical wind speed for elimination of the urban heat island. Source: Fuggle and Oke (1968).

under quite strong winds, with speeds of 15 to 25 mph being required for elimination in large cities.

Table II-6 gives values of the frequency of occurrence of inversions based below 500 feet for various American locations, after Hosler (1961). The figures are based on radiosonde data which were generally available only on a twice-daily basis. Consequently, the values given should be considered only as estimates. Apparently, Hosler did not take into account local factors such as topography. It is possible that this could have caused significant errors for some locations. The values are generally representative of suburban or semi-rural areas. According to Hosler, these figures agree closely in most cases with frequencies of inversions based on or near the ground. Figures included in Table II-6 for Edmonton are

TABLE II-6 - LOW-LEVEL INVERSION FREQUENCIES FOR VARIOUS LOCATIONS. SOURCE: HOSLER (1961)

Season	W	S	S	F	Season	W	S	S	F
Omaha	42	27	33	38	Detroit	25	34	55	49
Seattle	39	25	21	37	Bismark	42	28	29	37
Miami	24	15	13	22	Glasgow	48	33	32	44
New York	14	16	19	26	Washington	28	23	24	32
Denver	48	30	35	43	Pittsburgh	24	31	27	34
Los Angeles	56	30	19	44	Atlanta	38	31	29	38
Chicago	29	39	72	47	Edmonton[a]	57	37	33	49

[a]Edmonton data are not directly comparable to the other values (see text).

not strictly comparable to Hosler's data. These values will be discussed in another chapter. Hosler's data indicate considerable variation in atmospheric stability with location and season. Where local factors such as lakes do not play a part, inversion frequencies are, on the average, maximum in fall or winter, with a minimum in spring or summer when solar heating effects are greatest.

Table II-7 gives monthly mean wind speeds for various North American centers. Data are from the United States Weather Bureau (1962) and Canada Department of Transport (1968). About 75 per cent of the stations listed are located on the outskirts of urban areas; most of the remainder are well within the city. As previous discussed, these city values will generally tend to be lighter than those recorded in rural areas. Edmonton data are for the city airport. These data, in general, show a very definite seasonal pattern, with winds maximum in late winter or early spring, minimum in summer.

It is apparent from the inversion and wind-speed data above that the

TABLE II-7 - SEASONAL VARIATION IN WIND SPEED (MPH) FOR SELECTED NORTH AMERICAN STATIONS. SOURCE: CANADA DEPARTMENT OF TRANSPORT (1968) AND U.S. WEATHER BUREAU (1962)

Month	J	F	M	A	M	J
Edmonton	8.1	8.3	9.0	10.1	10.5	10.0
Winnipeg	12.4	12.1	12.9	14.2	13.8	12.0
Toronto	11.0	11.2	10.8	10.5	9.4	8.6
Halifax	15.5	13.7	14.6	13.0	11.4	10.2
Fairbanks	3.2	3.8	4.8	5.9	6.9	6.4
Seattle	7.8	8.0	8.6	8.3	7.7	7.6
Los Angeles	6.8	6.9	6.9	6.6	6.3	5.7
Denver	9.8	10.0	10.7	11.0	10.0	9.8
Omaha	11.4	11.8	13.2	13.7	11.8	11.0
Chicago	11.1	11.4	11.6	10.2	9.0	7.6
New York	11.1	11.1	11.3	10.8	9.0	8.4
Atlanta	11.4	11.8	11.8	10.9	9.1	8.4
Birmingham	9.0	9.5	10.0	9.2	7.6	6.7
Miami	9.3	9.9	9.9	10.2	9.1	8.1

Month	J	A	S	O	N	D	Yearly
Edmonton	8.9	8.5	9.6	9.1	8.8	8.2	9.1
Winnipeg	10.3	10.8	11.8	12.8	13.4	12.4	12.4
Toronto	7.7	8.4	9.1	10.0	10.0	9.8	9.7
Halifax	8.6	8.7	10.7	11.8	13.4	13.8	12.1
Fairbanks	6.0	5.8	5.6	5.1	3.8	3.1	5.0
Seattle	7.2	6.8	6.5	6.8	7.1	7.6	7.5
Los Angeles	5.4	5.3	5.3	5.7	6.5	6.8	6.2
Denver	9.0	8.6	8.6	8.6	9.5	9.8	9.6
Omaha	9.4	9.7	10.2	10.5	11.8	11.3	11.3
Chicago	7.8	7.6	8.7	9.4	11.4	11.0	10.1
New York	7.8	7.9	8.3	9.3	10.2	10.6	9.7
Atlanta	7.8	7.5	8.4	8.7	9.6	10.3	9.6
Birmingham	6.2	5.9	7.3	6.7	8.2	8.4	7.9
Miami	7.7	7.2	8.1	8.6	9.0	8.5	8.8

seasonal variations of these two factors are somewhat out of phase. If both factors are accorded equal importance in terms of atmospheric dispersion of urban pollution and heat, this mixing process would be, on the average, maximum in spring when winds are strong and inversion frequencies

generally low. The time of minimum mixing is more difficult to determine. It would appear to occur in late summer or early fall on the average. It would therefore be expected, on the basis of inversion frequencies and wind alone, that urban temperature excess would be minimum around March, and maximum about September.

Artificial Heat

Table II-8 gives United States Weather Bureau (1962) and Canada Department of Transport (1967) values of Heating Degree Days for various North American cities.

TABLE II-8 - HEATING DEGREE DAYS[a] FOR SELECTED NORTH AMERICAN LOCATIONS. SOURCE: UNITED STATES WEATHER BUREAU (1962) AND CANADA DEPARTMENT OF TRANSPORT (1967)

Month	J	F	M	A	M	J	J	A	S	O	N	D	Total
Edmonton	180	141	132	78	42	20	10	13	40	67	125	159	924
Winnipeg	202	165	147	79	38	14	4	6	36	68	124	172	1033
Toronto	131	115	97	59	28	8	1	3	15	43	73	113	671
Halifax	124	121	107	79	52	25	8	6	19	45	72	107	739
Fairbanks	232	190	174	108	55	19	15	30	61	116	186	230	1416
Seattle	75	60	56	39	25	11	5	5	13	33	54	68	444
Los Angeles	33	24	21	13	7	2	0	0	2	4	14	25	145
Denver	103	83	80	56	30	7	2	0	27	46	90	115	638
Bismarck	170	146	119	66	36	12	3	4	23	60	110	154	903
Omaha	130	106	83	39	18	3	0	1	9	33	78	116	616
Chicago	124	105	87	51	23	6	0	0	9	35	76	115	631
New York	130	91	75	44	13	1	0	0	11	25	55	90	497
Atlanta	63	52	40	13	20	0	0	0	1	11	39	61	283
Miami	6	5	1	0	0	0	0	0	0	0	1	5	18

[a]Values have been divided by ten. Base is 65°F. Units are °F.

These values are an index of the amount of space heating required. As would be expected, maximum values occur in winter. In summer months, these figures would indicate space heating in almost all localities to be negligible. The tremendous variation in space heating requirements from city

to city is also indicated. Yearly totals range from a low of 180 at Miami to 14,160 at Fairbanks. Such other sources as industry and motor vehicles may also provide a significant proportion of the city's heat. However, this will depend greatly on the climate and nature of industrial activity in a particular area. Of these various heat sources only space heating, as a rule, undergoes a significant seasonal trend. Taken alone it would indicate that the city's temperature excess should be greatest in winter, least in summer.

Pollution

Table II-9 gives mean seasonal variations of total particulate concentration and smaller suspended particles for the United States.

TABLE II-9 - SEASONAL VARIATION IN CONCENTRATION OF TOTAL PARTICULATE MATTER ($\mu gm/m^3$) AND FINELY SUSPENDED PARTICLES (COH/1000 LINEAR FT.) IN THE UNITED STATES. SOURCE: UNITED STATES PUBLIC HEALTH SERVICE (1966)

Month	1	2	3	4	5	6	7	8	9	10	11	12
Total P.	95	93	89	90	95	98	95	98	100	104	80	85
Fine P.	1.9	2.0	1.7	1.0	1.0	0.9	1.0	1.1	1.2	1.6	1.7	2.1

Data are from the United States Public Health Service (1966) National Air Sampling Network, which consists of over two hundred stations, about 85 per cent of which are urban. Total particulate concentrations show little seasonal variation, perhaps as a result of maximum background levels in summer balancing maximum urban production in winter. Finely suspended particles show a maximum in December, with an abrupt drop in early spring to a broad minimum centered about June. This pattern is probably a composite of above-described trends in atmospheric dispersion efficiency and domestic heating. It is unclear which of these two measures of particulate concen-

tration gives the best index of attenuation of incoming and outgoing radiation over the city. If there is any seasonal variation in this attenuation, it would apparently be maximum in winter, minimum in late spring. This is in accord with the previously discussed radiation attenuation measurements of Steinhauser and Emslie. In terms of minimum temperatures, maximum long-wave attenuation in winter would imply the greatest city excess in this season. The least excess should occur around June. It is difficult to make any definite statement about maximum temperatures.

Cloud

Cloudiness significantly affects city temperature excess at minimum temperature time, as can be seen in Table II-5. According to these data for Paris, a change from nearly clear to near overcast reduces city-country differences by roughly two thirds, the effect being greatest under light wind conditions. Work by Sundborg (1951) and Edmonds (1954), for Uppsala and Bonn respectively, indicated an average decrease of 1-2°C in night-time city temperatures for a change from clear to overcast skies. During the day, according to Edmonds, the effects of cloud were much less. Explanation of the effects of cloud, such as given in Table II-5, are difficult to assess without knowing how cloud cover is related to other climatic factors, such as temperature and stability. The inverse relationship between cloud and city temperature excess is perhaps a result primarily of two factors. First, clear skies at night are usually associated with intense surface cooling, and hence higher low-level stability. In addition, the relatively high rates of long-wave radiation associated with cloudless nights may accentuate the difference between city and country radiation loss caused by the interception of the radiation by buildings.

Table II-10, from United States Weather Bureau (1962) data, gives some indication of cloudiness for various North American cities. Edmonton data

were obtained by personal communication with the local forecast office. Units are percentage of total possible sunshine. These values should

TABLE II-10 - PERCENTAGE OF TOTAL POSSIBLE SUNSHINE FOR SELECTED NORTH AMERICAN STATIONS. SOURCE: UNITED STATES WEATHER BUREAU (1962) AND PERS. COMM. EDMONTON WEATHER OFFICE

Month	J	F	M	A	M	J	J	A	S	O	N	D	Mean
Edmonton	34	44	44	53	53	54	60	58	49	48	38	33	47
Seattle	28	33	42	47	52	49	63	56	53	36	29	24	45
Los Angeles	71	72	74	67	68	69	81	82	81	74	79	72	74
Denver	71	70	68	62	63	72	71	73	76	73	65	69	69
Bismarck	54	56	57	59	61	62	75	72	64	60	46	49	61
Omaha	54	54	52	59	60	65	76	71	69	68	53	48	62
Detroit	31	43	50	52	59	65	70	66	61	56	34	32	54
New York	50	56	57	59	61	65	66	64	63	61	53	50	59
Atlanta	47	51	56	65	69	67	62	66	64	67	58	48	60

give a reasonable idea of the seasonal trend in total cloud cover. With few exceptions, these figures indicate maximum cloudiness in winter, minimum in mid-summer, with a substantial difference between the the two extremes. On this basis alone, city temperature excesses should be greatest in summer, least in winter.

Snow Cover

There is a scarcity of data reflecting the effect of snow cover on city-country temperature difference. Treibich (1927) has computed values for Berlin as shown in Table II-11. It is apparent that city temperature

TABLE II-11 - THE EFFECT OF SNOW COVER ON CITY-COUNTRY TEMPERATURE DIFFERENCE. SOURCE: TREIBICH (1927)

Local Time	7	14	21
With snow	3.9	0.3	2.3°C
Without snow	1.7	0.4	1.0°C

excess, in this case, was generally much higher when snow was present. The exception occurred in the afternoon, when the difference was small. This small difference does not substantiate the previously-discussed theory that less extensive snow cover in the city acts to increase the city's temperature excess through decreased albedo. It is difficult to know whether Trebich's findings result from the snow cover as such, or whether they arise as a result of correlations between snow cover and other climatic factors.

Precipitation and Storage

It is impossible to make any definite statements on the effects of precipitation on city-country temperature differences. Rapid drainage may increase temperatures, as previously discussed. "Washout" of pollution may have the opposite effect, at least at night.

It is also difficult to define quantitatively the effect of storage of heat in the city upon its temperature. Presumably this effect will tend to decrease daytime temperatures and increase those at night. The effect will probably be greatest in summer when the largest amounts of energy are available.

Summary of Relevant Factors

A measure of the effects of wind, cloud cover and temperature on city-country temperature difference is given by regression equations computed by Sundborg (1951) for Uppsala and Edmonds (1954) for Bonn. Sundborg's work gave the following formula for daytime:

$$D = 1.4 - .01\ N - .09\ V - .01\ T - .04\ e$$

and for nighttime

$$D = 2.8 - .10\ N - .38\ V - .02\ T + .03\ e$$

where: D is city-country temperature difference in °C

N is cloudiness in tenths of sky covered

V is wind speed in m/s

T is temperature in °C

e is vapour pressure in mm. Hg

The equivalent equation for Bonn for daytime was:

$$D = 1.72 - .03\ N - .13\ V - .10\ e + .03\ T$$

and at night:

$$D = 3.05 - .18\ N - .18\ V + .17\ e - .18\ T$$

For day and night conditions at both locations it is apparent that wind was a major determining factor of temperature difference. Cloud cover was also of importance during the night, but in daytime its significance was much less. For Uppsala, the influence of temperature was small. In Bonn, temperature was more important, especially at night when cold weather tended to enhance the city's temperature excess.

Table II-12 partially summarizes the previously-discussed seasonal variation of different factors influencing city temperature. Time of the

TABLE II-12 - ESTIMATED TIME OF YEAR WHEN VARIOUS FACTORS ACT TO MAXIMIZE AND MINIMIZE CITY-COUNTRY TEMPERATURE DIFFERENCES[a]

	Maximize	Minimize
Wind	Aug	Mar
Stability	Dec (w) Sep (e)	Jun (w) Mar (e)
Dispersion (wind and stab.)	Oct (w) Sep (e)	Apr (w) Mar (e)
Temperature (space heating)	Jan	Jul
Pollution	Jan	May
Cloud	Aug	Jan
Storage	Jul	Jan

[a]Estimates based on North American cities previously listed.

w = west, e = east.

year in which each parameter is most, and least, influential in enhancing city-country differences is given, based on the data previously discussed in this chapter. The months given are tentative, and should be considered as approximations. The typical seasonal pattern of minimum city-country temperature difference in spring coincides roughly with the windiest, most unstable time of the year, when dispersion of city effects should be maximum. Fine-particle pollutant concentrations are low at this time. Space heating and cloudiness are about half way between their maximum and minimum values. The maximum city-country difference typically found in fall coincides roughly with the period when atmospheric dispersion would be expected to be minimum. Fine-particle pollution is still relatively low at this time. The secondary (or sometimes primary) maximum in the difference that occurs in winter coincides with a maximum in space heating, and in fine-particle pollution concentrations. City-country differences in snow cover probably contribute to this mid-winter maximum.

Tentatively then, it would appear that the seasonal pattern of city temperature excess is dependent to a major extent on wind and stability. The effects of space heating, snow cover, and perhaps pollution, may in some localities be sufficient to displace the typical fall maximum difference to winter.

CHAPTER III

THE EDMONTON AREA

The City of Edmonton

The city of Edmonton is located in central Alberta at 54' North, 113' West, on the northern extremity of the Great Plains. The surrounding country is reasonably flat, except for occasional river valleys and ravines. Elevations vary between about 2,100 feet and 2,500 feet, with the differences arising mainly from gentle slopes. The land is primarily agricultural with trees covering, on the average, about 14 per cent of the area.

The city itself is located on the North Saskatchewan River, which runs roughly southwest-northeast through its center, as indicated in Fig. III-1. The river valley is generally less than a mile wide, and about 200 feet deep. The remainder of the city slopes very gradually toward the river, at a rate of about 20 feet per mile. Excluding the river, the only body of water of any significant size in the area is Big Lake, about 6 miles northwest of the city and about 9 square miles in area. The city is approximately square in shape, currently covering about 60 square miles. The central business district is located roughly in its center.

Edmonton, the capital of Alberta, is a major distribution center, with extensive offices and other facilities connected with the oil industry. The major industries that do exist in the area are primarily those connected with petroleum refining or related chemical processes. They lie for the most part to the east and northwest of the city, generally

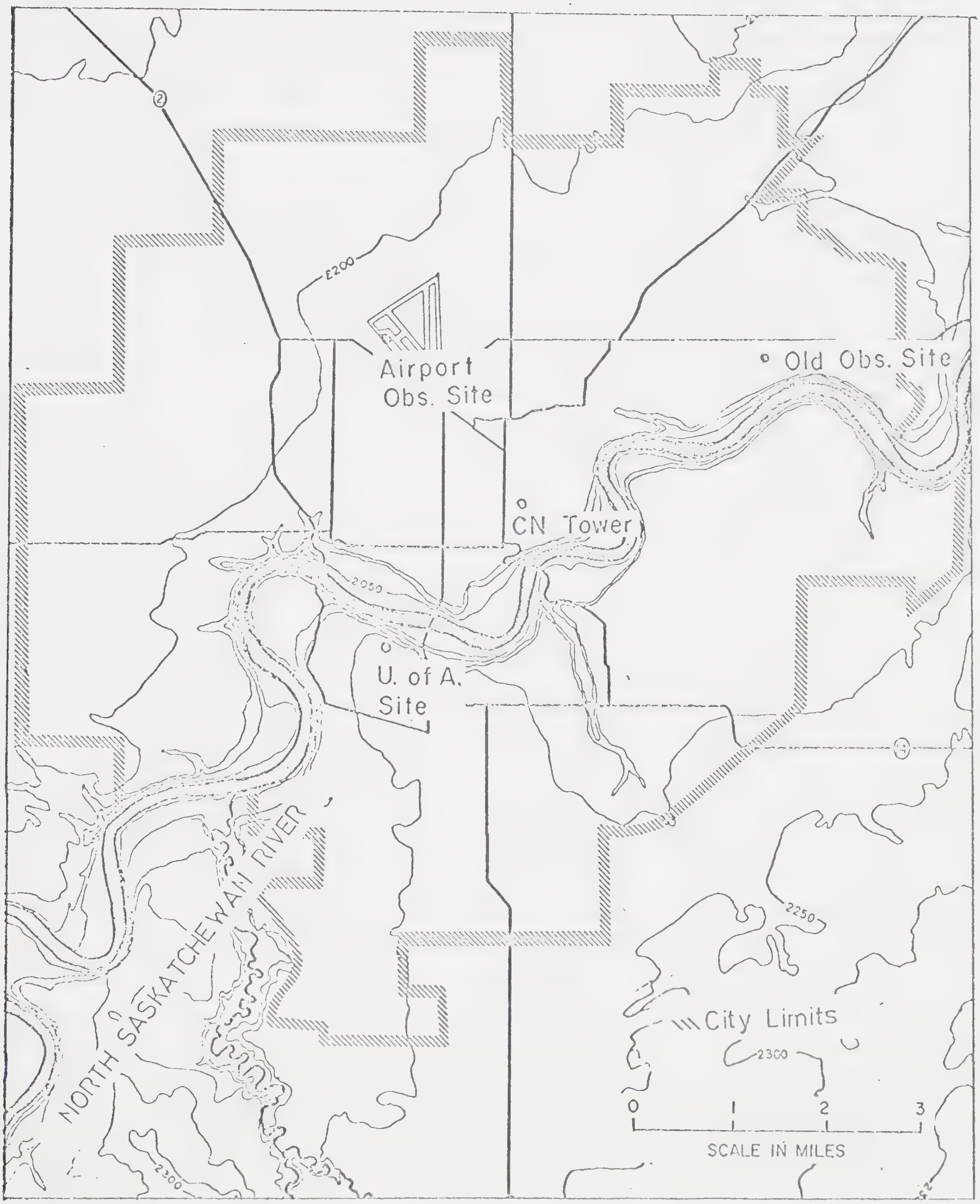

Fig. III-1. The city of Edmonton, showing various observing sites.

at a distance of about 6 miles from the central business district.

Population density of the city is generally light (less than 50 persons per acre) except in the city core which is classified as moderate density (50-89 persons per acre). Heights of buildings are typical for a city of Edmonton's size, with the majority of buildings over four storeys in an area extending from the central business district westward, near the river, for about 3 miles.

Edmonton has been one of the fastest growing North American cities since the late 1940s. The last 20 years have seen a population increase of about 200 per cent, to 440,000 people. Prior to 1945, the growth rate was roughly constant at about 20,000 people per decade. Figure III-3 indicates the trend. Information giving the physical extent of the built-up portions of the city is difficult to obtain for earlier periods. Fig. III-2 gives approximate boundaries in 1910, 1957 and 1967. Data were obtained from a variety of sources.

After 1917, the meteorological station in Edmonton was located about 3 miles northeast of downtown in a residential area near what was then the eastern edge of the city (see Fig. III-1). In 1937, observations began at a location on the southwestern edge of the Industrial Airport, about 2 miles northwest of downtown. Observations have been taken continuously at this latter station up to the present time. After a short period of simultaneous operation, the old station was closed. There was no appreciable difference in elevation between the locations of the two stations. Both were at about 2,180 feet.

The airport at which the observing station is currently located covers about 1 square mile and is approximately square in shape. From the observing station, the city currently extends north and west about 2.3 miles. To the southeast, the extent is about 5.5 miles. The airport area is typical

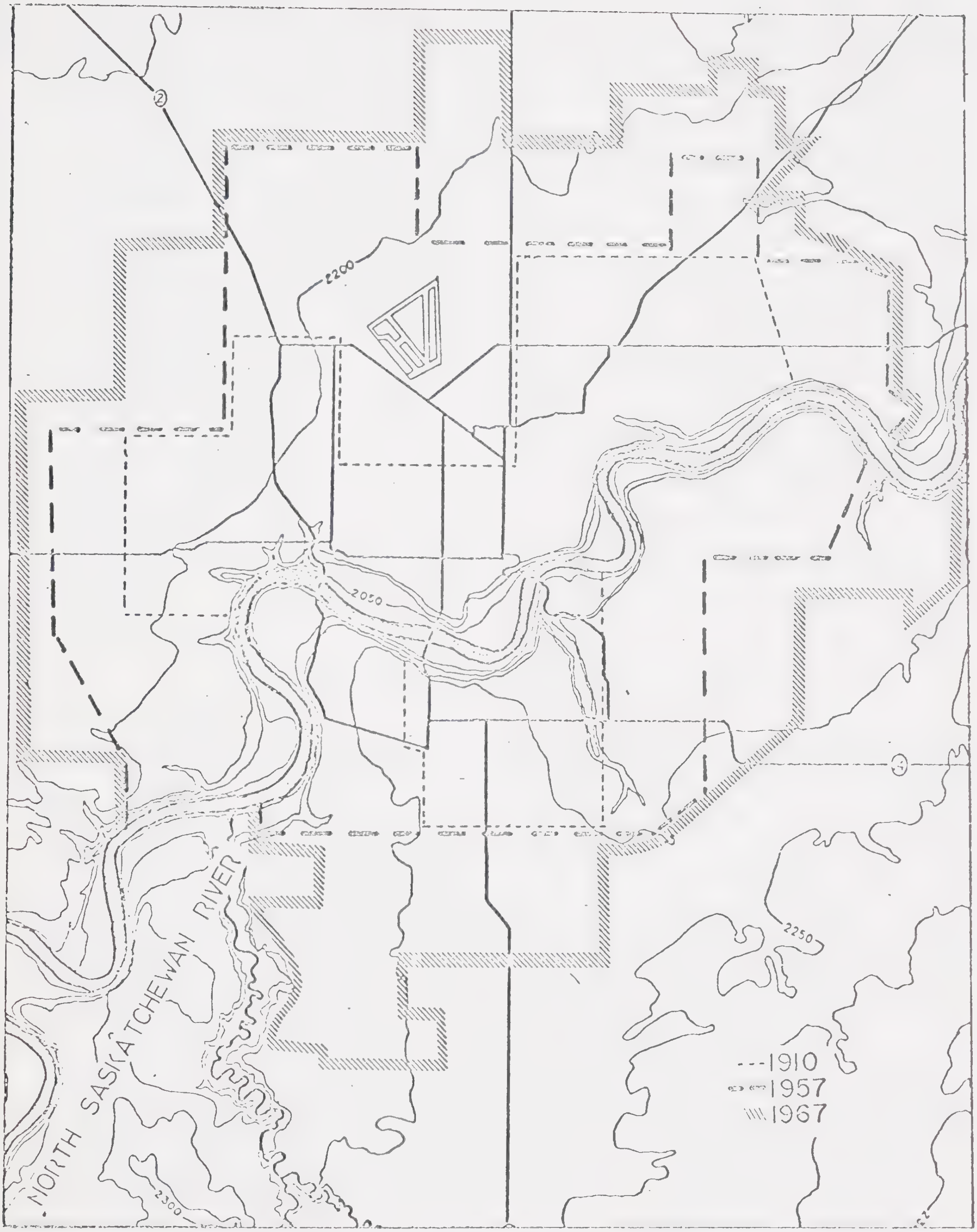

Fig. III-2. Estimated extent of developed areas of Edmonton, for various periods.

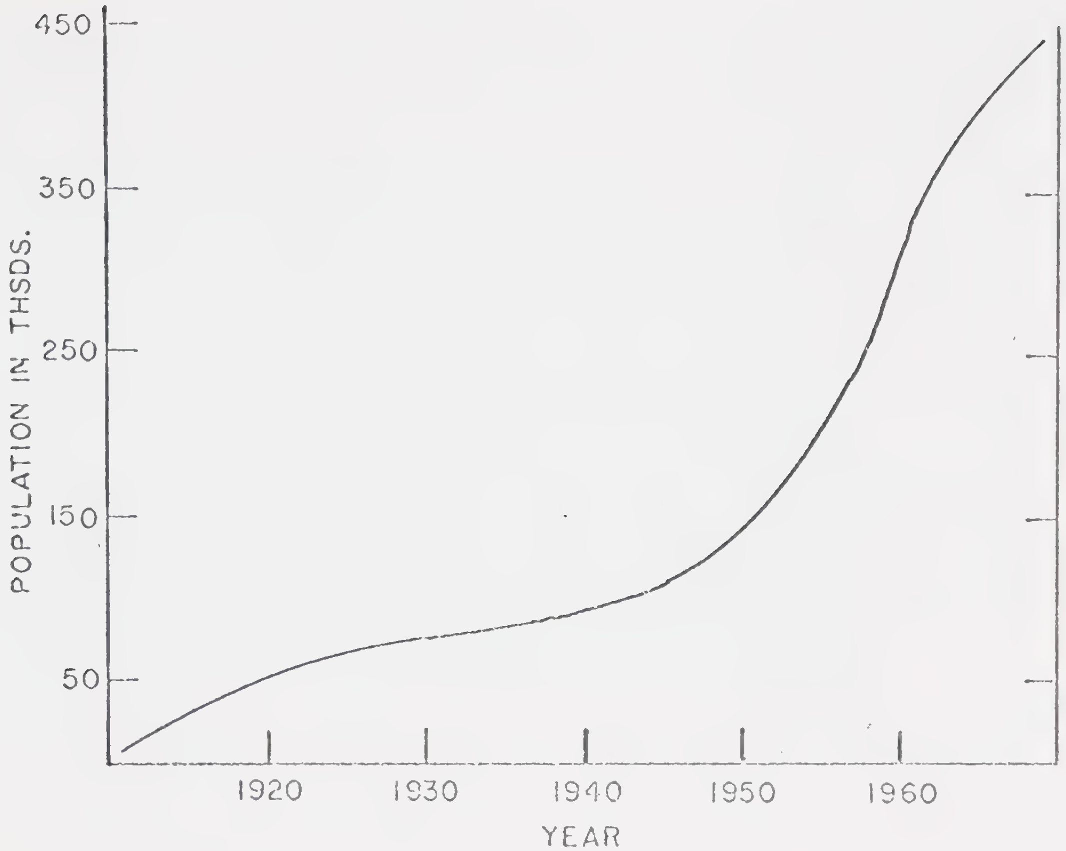

Fig. III-3. Growth in population of Edmonton.

of much of the city in that it slopes very gradually toward the Saskatchewan River (southeastward) at a rate of about 20 feet per mile. In the immediate vicinity of the observing instruments there is a moderate concentration of commercial establishments and airport facilites, except toward the northeast, where only the two-storey administration building separates the site from the open expanses of runway. Extensive vehicular traffic is present about 200 yards to the southwest of the site. Most buildings in the area are two to three storeys in height. A taxiway immediately north of the administration building could conceivably bring the instruments under the influence of aircraft exhaust in a few instances, although no concrete evidence of this could be found.

Wetaskiwin and Calmar

Wetaskiwin and Calmar observing sites were used for comparison purposes.

Wetaskiwin is located 40 miles south-southeast of Edmonton. The surrounding countryside is similar to that of Edmonton--nearly flat, agricultural, and about 15 per cent tree covered. The elevation is about 2,500 feet, or about 320 feet higher than Edmonton. Wetaskiwin's population trend is given in Table III-1. There was little growth in the town until after

TABLE III-1 - POPULATION OF WETASKIWIN

Year	1921	1931	1936	1941	1946	1956	1961	1966
Population	2061	2125	2058	2318	2645	4476	5300	6000

World War II. Since that time, population has increased from about 2,500 to the present level of around 6,000. A canning plant and facilitiesfor the manufacture of camping equipment constitute the only industries in the town. Both enterprises are small. The city is roughly square, covering about 1.5 square miles. The observing station was moved from the south end of the city to its present site, a few blocks southwest of the central business district, in 1928. The instruments are located in a back yard of an older residential area, which has seen little change since World War II. (See Fig. III-4 and Fig. III-5.) Observations have been taken by the same individual since 1928, except for the period 1940-45.

The Calmar observing site is located on a farm in a completely rural setting, about 20 miles southwest of Edmonton. The land is nearly flat, sloping at a rate of about 25 feet per mile toward the Saskatchewan River, which lies about 4 miles north. The observing site is located near the house and barn, which are largely surrounded by windbreaks consisting of thin lines of original-growth trees (see Fig. III-6 and Fig. III-7). The site has been in the same location since 1917, except for short breaks in the summer when the instruments were sometimes moved to an adjacent

Fig. III-4. Wetaskiwin observing site, looking east.

Fig. III-5. Wetaskiwin observing site, looking south.

Fig. III-6. Calmar observing site, looking west.

Fig. III-7 Calmar observing site, looking [illegible].

farm during vacations. Two individuals have served as observers, the change occurring in 1947.

Climate of Edmonton

The Edmonton area, according to Köppen's classification, has a cool snow-forest climate with warm summers. In fact, Edmonton vies with Winnipeg for the distinction of being North America's coldest major city. Mean temperatures for a representative selection of Canadian and United States cities are given in Table III-2, from United States Weather Bureau (1962) and Canada Department of Transport (1968) data. Edmonton is, on the average, about 15°F colder than the median temperature for these centers,

TABLE III-2 - MONTHLY MEAN TEMPERATURES FOR SELECTED NORTH AMERICAN LOCATIONS. SOURCES: UNITED STATES WEATHER BUREAU (1962) AND CANADA DEPT. OF TRANSPORT (1968)

Month	J	F	M	A	M	J	J	A	S	O	N	D	Mean
Edmonton	7	11	22	40	52	58	63	60	52	41	25	13	37
Winnipeg	0	4	18	38	52	62	68	66	55	43	23	9	37
Toronto	20	21	30	43	56	65	70	68	61	50	39	26	45
Halifax	26	26	32	40	50	58	65	66	60	51	42	30	45
Fairbanks	-10	-3	9	29	47	59	61	56	45	28	3	-9	26
Seattle	40	44	47	52	57	62	66	65	61	54	47	43	53
Los Angeles	55	56	59	62	65	68	73	73	71	67	62	57	64
Denver	29	32	38	48	56	66	73	72	63	52	40	32	50
Omaha	23	27	38	52	63	73	79	76	67	56	39	28	52
Chicago	25	27	37	48	59	69	75	73	66	54	40	28	50
Detroit	26	27	35	46	58	68	73	71	64	53	40	30	49
New York	33	33	41	51	62	71	76	74	68	58	47	36	54
Washington	36	37	45	54	65	73	77	75	70	58	48	38	57
Atlanta	45	47	53	62	70	78	80	79	74	63	52	45	62
Miami	68	69	71	75	78	81	83	83	82	78	72	69	76

the difference being greatest in winter, least in spring. The low temperatures result primarily from the city's high-latitude location, and its easy accessability to relatively unmodified, southward-moving Arctic air masses.

For similar reasons, the frequency of stable atmospheric conditions over the area is high. Table II-6 (Chapter II) compared inversion frequencies between Edmonton and Hosler's values for selected United States cities. The Edmonton values were derived from tables constructed by Djurfors (1969), based on temperature profiles between 46 feet and 343 feet on the CN Tower near downtown Edmonton. Data were for the period August 1967 to July 1968. Differences between Hosler's figures and those of Djurfors may have resulted from differences in the nature of the locations. The American data are representative of suburban or semi-rural areas, and consequently should be less subject to urban influences. The most important effect in this respect is probably the decrease in stability due to higher city temperatures. As a result, Djurfors' figures probably underestimate inversion frequencies, relative to the other locations.

Even under the assumption that Edmonton values are not, relatively speaking, too low, it is apparent that inversion frequencies for Edmonton are high at all times of the year. This is especially true in fall and winter when no values listed in Table II-6 exceed the Edmonton values. The seasonal variation for Edmonton shows a maximum in January, a minimum about June, similar to most western cities. Monthly vertical temperature gradient figures are given in Table III-3. These figures, based on 10 years of radiosonde data from the Edmonton area, give average vertical temperature gradients between the surface and about 1,700 feet. Included in the table are figures, based on Djurfors' analysis of one year of data, giving city vertical temperature gradients for daytime and night. Although these latter values represent a relatively small sample, it is possible to discern the seasonal trend. The daytime values are somewhat similar to the

TABLE III-3 - VERTICAL TEMPERATURE GRADIENT DATA FOR EDMONTON AREA (°C/100M). SOURCES: DJURFORS (1969) AND CANADA DEPT. OF TRANSPORT (1965)

Month	J	F	M	A	M	J	J	A	S	O	N	D
0500 & 1700 MST[a]	0.8	0.4	-0.2	-0.5	-0.9	-0.9	-0.7	-0.6	-0.4	0.0	0.2	0.7
0900-1800 MST[b]	0.8	-0.1	-0.2	-0.4	-1.1	-1.2	-1.2	-1.1	-0.6	-0.2	0.0	0.1
2200-0500MST[b]	1.2	1.0	0.5	0.2	0.9	0.8	1.0	1.8	2.0	0.5	0.9	0.5

[a]Ten-year radiosonde mean for lowest 1700 ft.
[b]One year's data for CN Tower (15-113m).

long-term mean values, although there is a tendency for stability to remain consistently low from late spring through late summer. The nighttime values are somewhat different in nature, with a maximum in late summer, as well as winter. In this case the minimum stability occurs about April. It is to be noted that even the least-stable nighttime values still represent inversion conditions.

In spite of its location on nearly flat agricultural land, Edmonton's winds are quite light on the average. Comparison with other cities listed in Table II-7 (Chapter II) indicates that, of thirteen, only four have lighter winds on a yearly average. Edmonton and Fairbanks are the only cities listed that differ significantly from the typical seasonal pattern in that minimum winds occur in winter instead of summer. The January minimum at Edmonton coincides with the period of maximum inversion frequencies. The city retains a spring maximum with a secondary minimum in August.

Table III-4 gives speed and percentage frequency of winds by direction. Data are from Canada Department of Transport (1968). The preferred wind direction is south except in summer, when northwest winds are prevalent. On the average, winds from the south and southwest are

TABLE III-4 - PERCENTAGE WIND FREQUENCY FOR EDMONTON INDUSTRIAL AIRPORT. SOURCE: CANADA DEPT. OF TRANSPORT (1968)

Direction	N	NE	E	SE	S	SW	W	NW	Calm
Jan.	9	9	7	8	20	13	13	16	2
Apr.	12	11	8	14	19	8	11	14	2
Jul.	11	8	8	10	12	11	17	20	2
Oct.	8	4	4	10	24	17	15	16	2
Yearly Speed	10.9	8.4	7.9	9.8	7.7	6.4	8.5	11.4	...

lightest, while those from the north and northwest are strongest. This relationship between speed and direction is generally consistent throughout the year. Winds from southeast to southwest give the air a relatively long trajectory over the city prior to its arrival at the observing site.

The diurnal variation in wind speed for summer (July, August, and September) and winter (December, January, and February) is given in Fig. III-8 for three Edmonton area locations, after Hage and Longley (1968). Nisku is an airport site located in a rural area about 15 miles south of the city. The University of Alberta values are from a high-level (63 meters) site about 2 miles southwest of the city center (see Fig. III-1). The height of the Edmonton city anemometer is 18 meters, representing a considerable departure from the 10-meter exposure of the Nisku site. Data are for 5 years in the case of Nisku and Edmonton, 2 years for the University.

It is apparent from these comparative wind data that the diurnal variation of wind in winter is surprisingly small, presumably because of the high degree of stability which persists at all hours during this season. A winter daytime minimum in the higher-level winds, corresponding to an increase in those at a lower level in the city, is probably

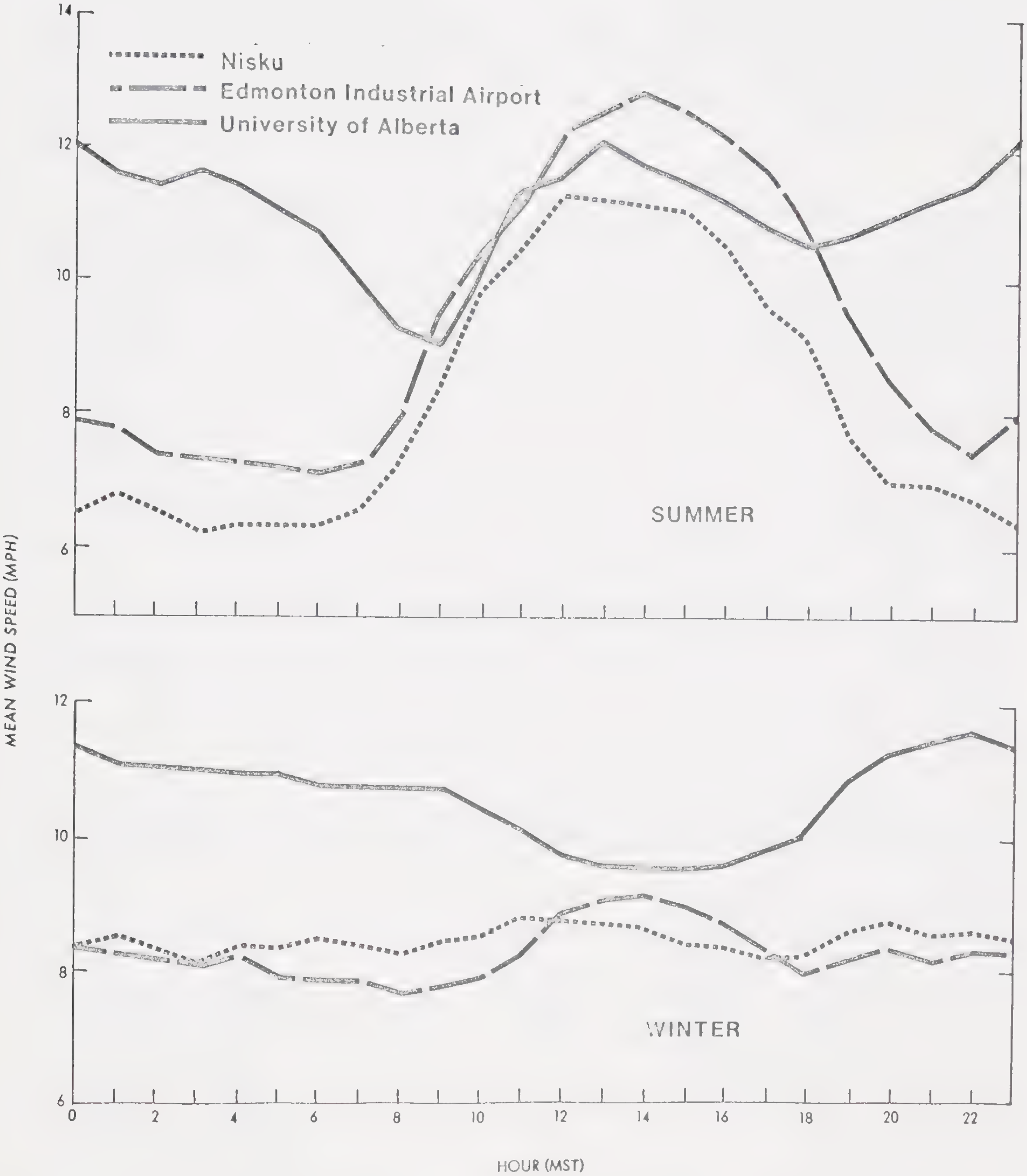

Fig. III-8. The diurnal variation in wind speed at a height of 18 meters in Edmonton (airport), at 10 meters in a rural site (Nisku), and at 63 meters in the city (University of Alberta). Data are for 5 years, except for 2 years at the University. Source: Hage and Longley (1968).

indicative of the occurrence of some vertical mixing, in spite of the high average stability in this period. It is also apparent from Fig. III-8 that there was, on the average, no distinct indication that city winds were lighter than their rural counterparts, as is often the case. The difference in heights of the wind recording equipment casts doubt on the validity of this type of comparison, however.

In summary, comparison of wind and stability data for Edmonton with similar data presented for other North American cities indicates that, relatively speaking, atmospheric dispersion rates over the city are probably low. This is especially true in winter.

Pollution

In spite of the poor dispersion ability of the atmosphere over Edmonton in winter, particulate pollution levels are low for a city of its size. Table III-5 gives total particulate concentrations and soiling index values for Edmonton, from data collected by the Alberta Department of Health (1968). The samples were taken in the downtown area.

TABLE III-5 - TOTAL PARTICULATE AND FINE PARTICLE CONCENTRATIONS FOR EDMONTON, 1964-68. SOURCE: ALBERTA DEPT. OF HEALTH (1968)

Season	W	S	S	F	Yearly
Total particles[a]	63	119	95	94	94
Fine particles[b]	0.44	0.30	0.22	0.28	....

[a]units - $\mu gm/m^3$.

[b]units - COH/1000 linear ft. (soiling index).

Comparison of the Edmonton figures with the NASN means given in Table II-9 (Chapter II) indicates that, on a yearly basis, the city's total particulate concentration is about 78 per cent of the mean value

for urban areas of equivalent size. It is only about one half the mean concentration for large cities of over two million people. The distinct winter minimum in total particles in Edmonton is not observed in the NASN mean values. Fine-particle concentrations for Edmonton are much lower than the average values given in Table II-9, although the seasonal trend giving a winter maximum remains evident.

The low levels of pollution that exist in Edmonton in spite of the relatively poor atmospheric dispersion are probably a result of the extensive use of natural gas in the city (which on combustion produces negligible particulate matter) combined with the relatively small number of industries, especially within the city proper. Another factor may be the high latitude of the city, which reduces photochemical reactions in the air to relatively low levels. Rolston (1964) has calculated that 80 per cent of urban production of particulate matter in Edmonton results from industrial activity, 19 per cent from incineration. Space heating, automobiles and other sources are, therefore, almost negligible. Consequently, Rolston's findings would imply that the seasonal variation in urban particulate emission rates should be small. The winter minimum in total particulate concentration is probably a result of low entrainment rates of surface material in this season. A long period of snow cover and light winter winds probably account in part for these low rates. Fine-particle concentrations are probably more closely related to urban sources, showing a maximum in winter as a result of low dispersion rates over the city.

Fine-particle concentrations over the city show a maximum, generally speaking, for winds from south and southeast. Minimum quantities are for winds from northwest through northeast. Although these values are

undoubtedly related to the relative orientation of emission sources, the fact that stations located in different parts of the city tend to give the same pattern would indicate that the relatively light speeds and higher values of stability associated with southerly winds probably play a part.

City Energy Sources

The very high number of Heating Degree Days for Edmonton (see Table II-8, Chapter II) is indicative of the large amount of space heating required in the city. This heat source will be strongly temperature dependent, as indicated by data from Robertson (1955), who computed the city's natural gas consumption in cold weather as a function of temperature. As can be seen from his values, as indicated in Fig. III-9, a decrease in temperature from 10°F to -30°F served to increase gas consumption by about 50 per cent. No figures were available for the industrial production of heat in the area, but in view of the fact that major industries are small in number and generally located on the city's periphery, it is probable their contribution is not large. Heat released from automobiles cannot be discounted as an energy source in the city. Daniels (1965) suggests an average figure of 2.5×10^5 BTU per hour per vehicle.

From natural gas consumption rates obtained through personal communication with Northwestern Utilities, Daniels' figure for automobile traffic, and radiation data from Canada Dept. of Transport (1967), it is possible to compute the relative amounts of artificial and solar energy received in Edmonton over the year. It cannot be emphasized too strongly that these energy values are only rough approximations, because of a number of unknown factors. The worst difficulty is with the city's albedo, especially in winter. From a variety of sources, a value of

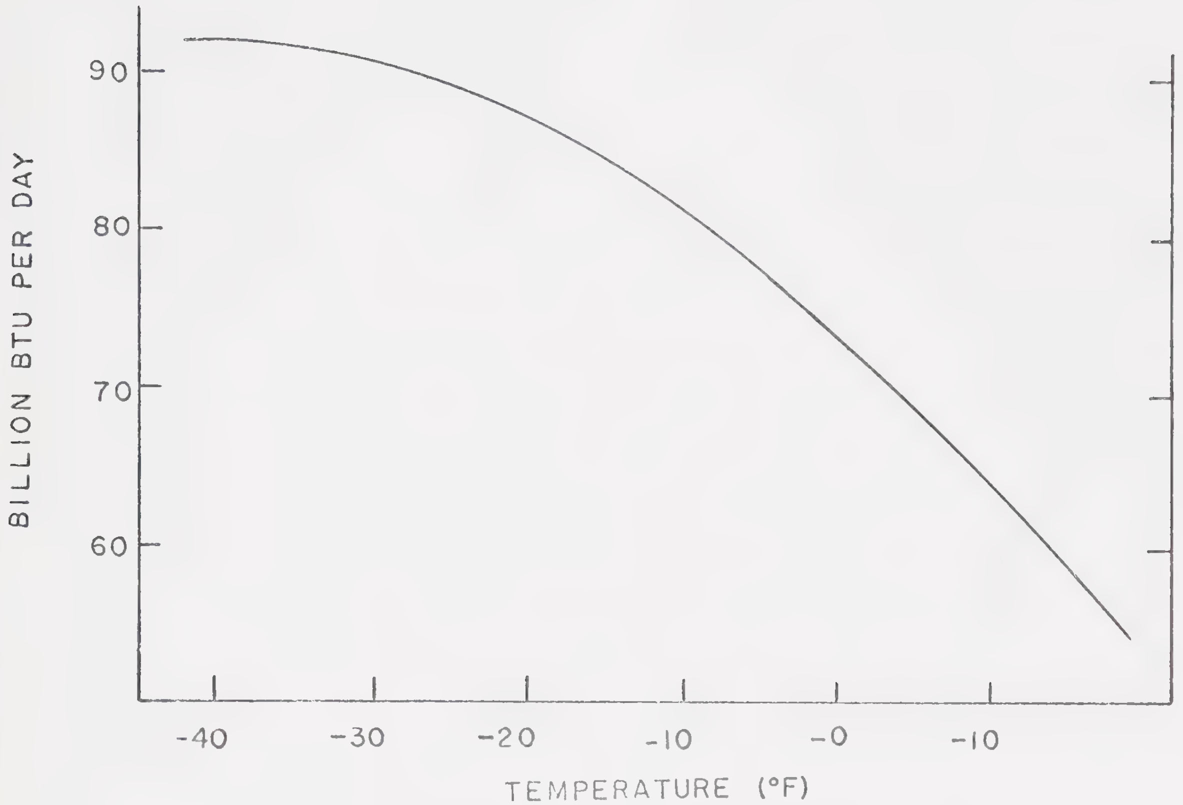

Fig. III-9. Energy production in Edmonton from the combustion of natural gas, as a function of temperature. Data are for a population level of 160,000. Source: Robertson (1955).

0.15 was chosen for albedo, except in winter when it was increased to 0.50 to account for the partial snow cover over the city. The results of these computations are shown in Fig. III-10. In summer the proportion of heat received from artificial sources is probably less than 10 per cent of the total. The maximum in the ratio of artificial to solar energy is probably reached in December, when the two sources are, speaking very roughly, equal.

Other Climatic Factors

Occurrence of persistent fog over any appreciable area of Edmonton is uncommon for temperatures above 0°F. However, at temperatures considerably below 0°F, its occurrence becomes quite frequent. Robertson (1955) has calculated that, for a time in which the city's population

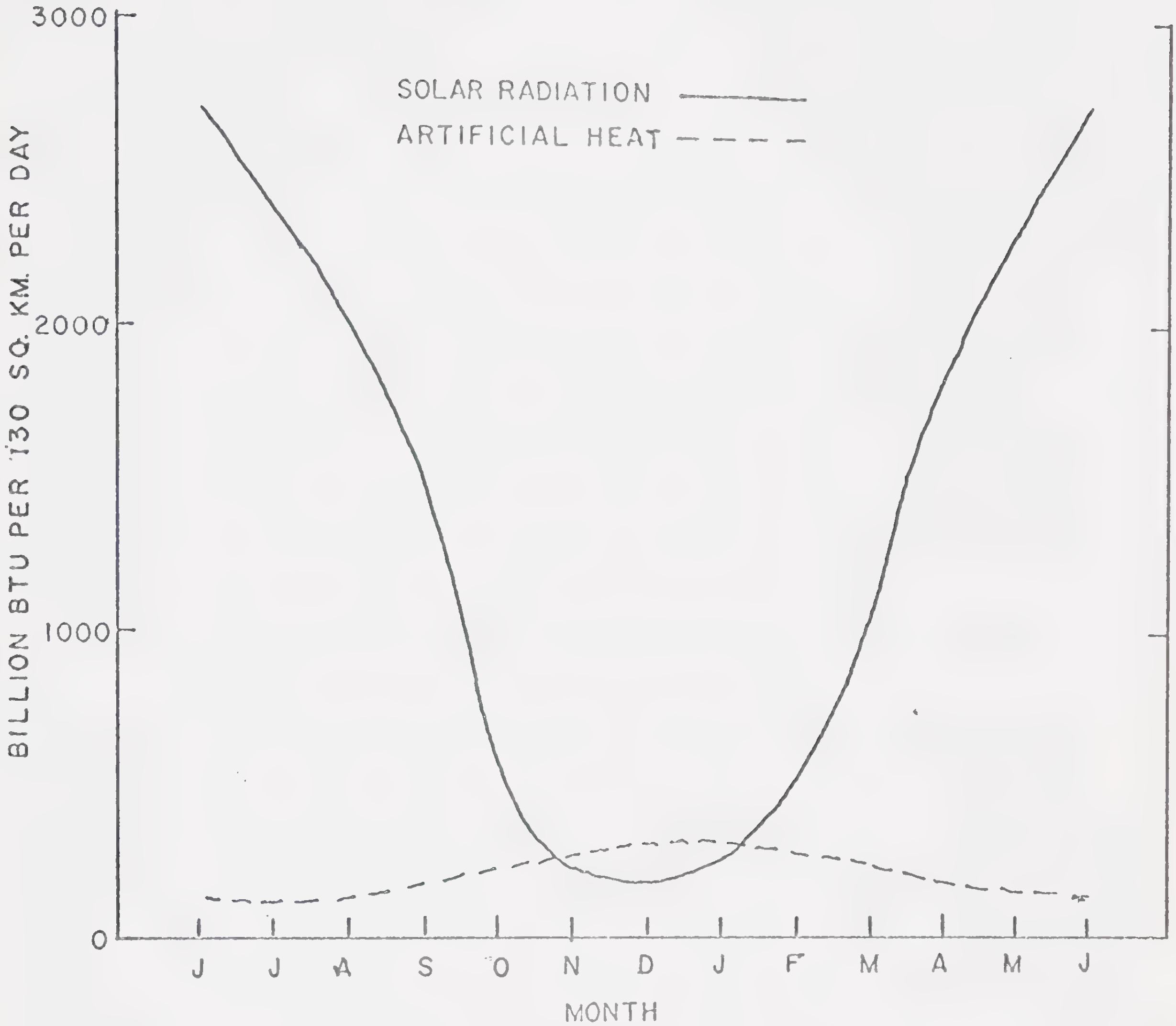

Fig. III-10. Estimated contributions of insolation and artificial heat (natural gas combustion and automobiles) to the energy budget of Edmonton.

was only 40 per cent of the present figure of 440,000, visibilities of less than 6 miles occurred about 40 per cent of the time in which temperatures were below 0°F. The fact that this fog is related to urban influences is indicated by Robertson's figures for a rural station in the same region, where the equivalent fog frequency was only 7 per cent. Winds of 2 to 7 mph from a southerly to southwesterly direction gave the highest frequencies of fog.

Table III-6 (Canada Dept. of Transport (1966)) gives mean monthly cloud amounts for selected Canadian stations. These data, and the values of percentage of total possible sunshine given in Table II-10 (Chapter II), indicate that, in summer, Edmonton has relatively large

TABLE III-6 - MEAN MONTHLY CLOUD AMOUNTS[a] FOR SELECTED CANADIAN CITIES. SOURCE: CANADA DEPT. OF TRANSPORT (1966)

Month	J	F	M	A	M	J	J	A	S	O	N	D	Mean
Edmonton	6.5	6.4	6.4	6.4	6.4	6.7	5.8	5.7	5.7	5.9	6.3	6.4	6.2
Vancouver	8.0	7.5	7.1	6.8	6.4	6.8	4.8	5.1	5.4	7.1	7.9	8.1	6.8
Winnipeg	5.8	5.4	6.0	6.0	6.1	5.4	5.1	5.3	6.0	5.7	7.2	6.3	5.9
Toronto	7.3	6.8	6.3	6.2	6.3	5.7	5.0	5.1	5.3	5.6	7.3	7.3	6.2
Halifax	7.0	6.6	6.4	6.8	6.8	7.0	6.4	6.2	5.7	5.8	7.1	7.0	6.6

[a]Units are tenths of sky covered.

amounts of cloud. In winter, the city's cloud cover is more typical of the amounts in other locations. In spite of the extensive summer cloud, precipitation amounts are relatively small, with a yearly total of only 19 inches.

The Nature of the Heat Island at Edmonton

Some idea of the relationship between stability and the heat island in Edmonton can be gained from Fig. III-11, after Hage and Longley (1968). This diagram shows, for a winter month and a summer month, temperature

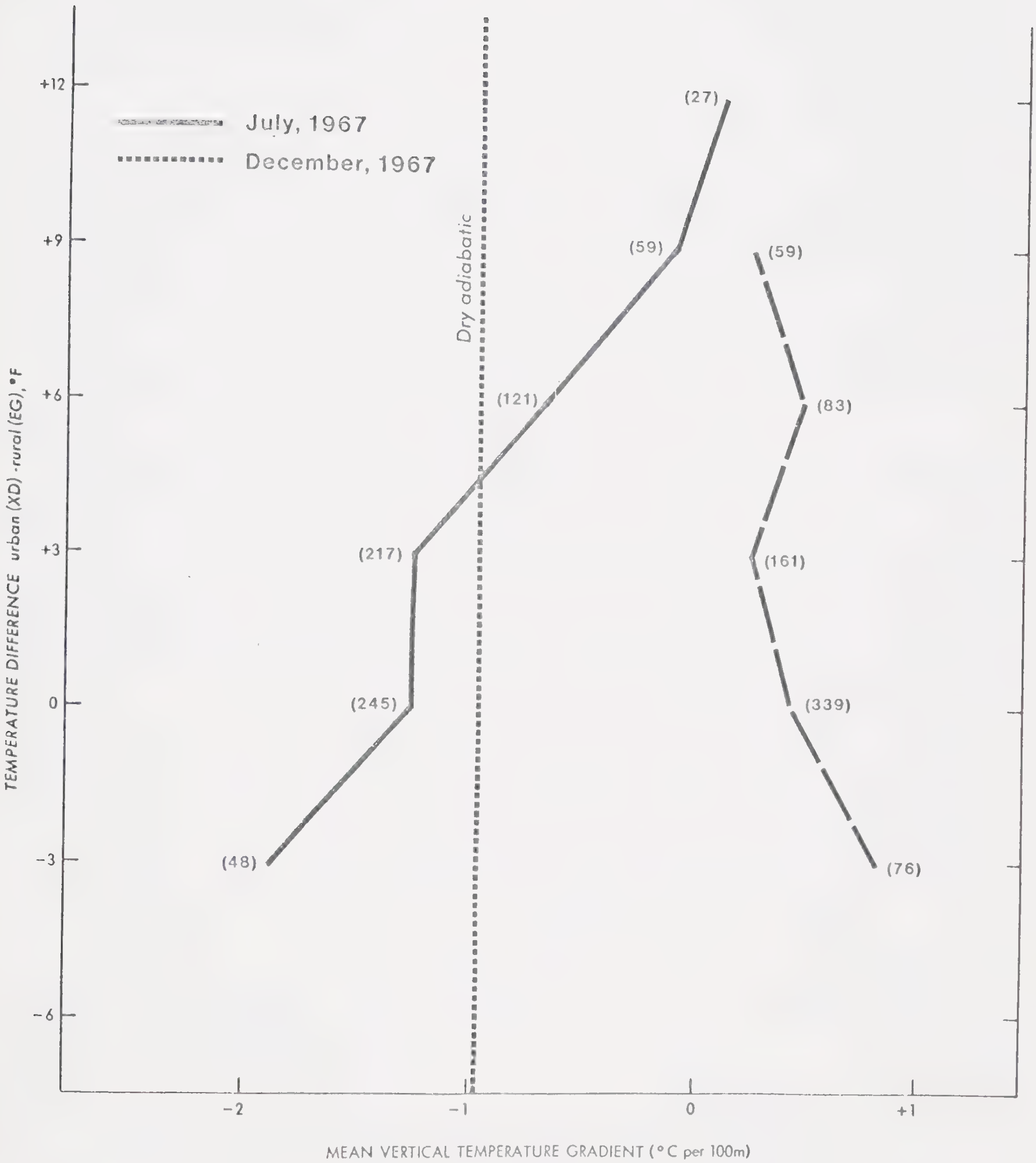

Fig. III-11. Stability, as measured on the CN Tower near downtown Edmonton, as a function of city-country temperature difference. Numbers in brackets indicate number of observations. Source: Hage and Longley (1968).

difference between Edmonton airport and the rural Nisku station as a function of vertical temperature gradient between 17 meters and 57 meters on the CN Tower near downtown Edmonton. Assuming the Edmonton-Nisku temperature difference gave a valid measure of city temperature excess, it is apparent that in summer the city-country difference was closely related to stability, with the most stable conditions being associated with a large difference. It would be unwise to consider this as a strict "cause-and-effect" relationship. For example, the fact that low city-country differences occurred in early afternoon coincident with relatively unstable conditions resulting from solar heating does not guarantee that instability was the primary cause of these small differences.

In December there was little relationship between Edmonton-Nisku differences and stability. Highly-stable conditions were reported for all differences. In a number of cities, it has been found that city heat acts to strongly modify inversion conditions and hence promote mixing. These data do not substantiate the occurrence of such a process in Edmonton. This does not necessarily imply that mixing over the city does not occur to some degree, however. As discussed previously, Fig. III-8 gives evidence of daytime mixing in winter.

The diurnal variation in city-country temperature differences for Edmonton is indicated in Fig. III-12, after Hage and Longley (1968). The diurnal trend in differences was quite similar to the typical values given in Table II-3 (Chapter II). In July, the maximum difference occurred in late evening, with the difference remaining large through the night, to minimum temperature time. Differences were small during the late morning, and then began increasing again by afternoon. In December, the city-country difference at minimum temperature time was

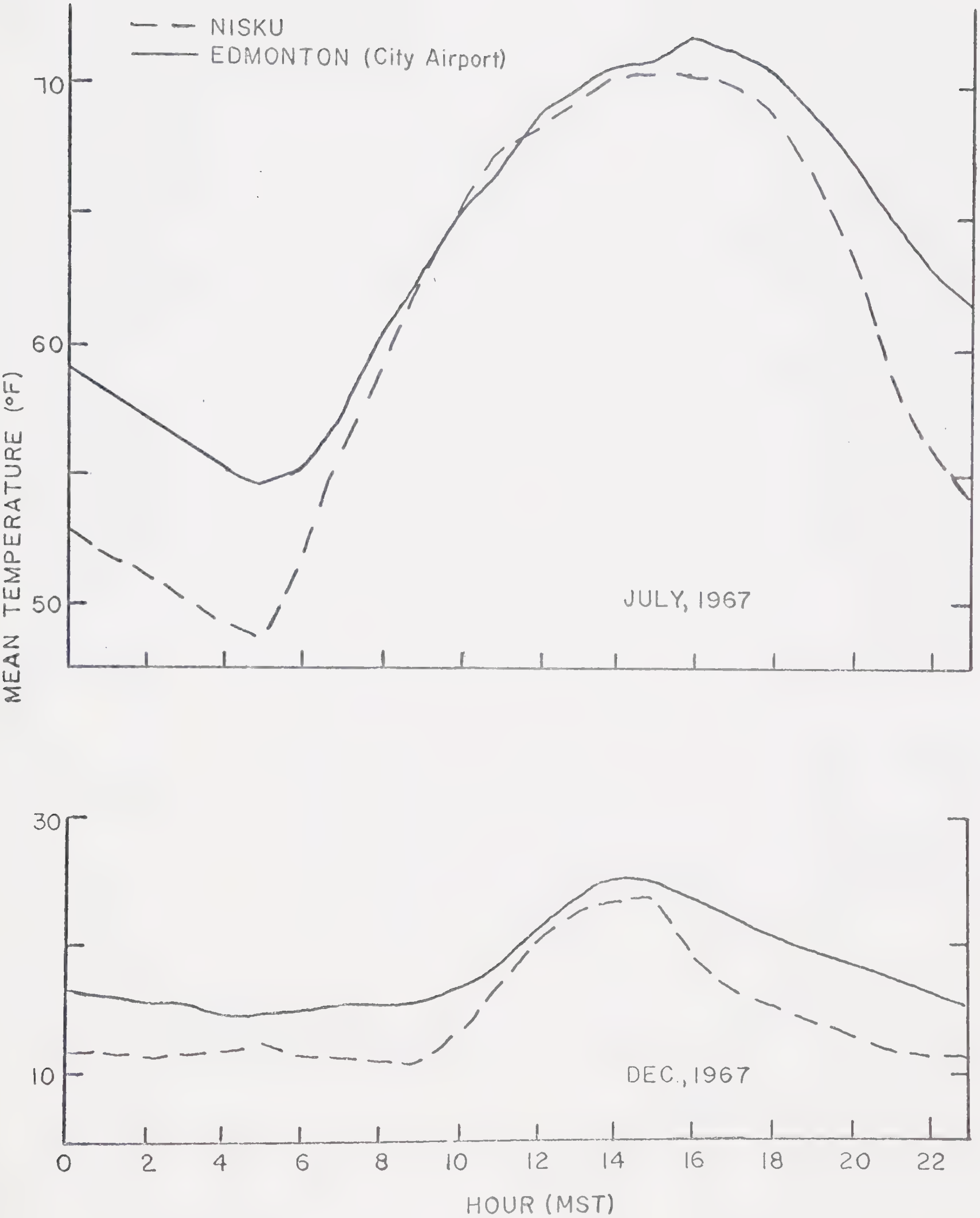

Fig. III-12. Diurnal temperature variation in Edmonton, and at a nearby rural station. Source: Hage and Longley (1968).

slightly less than its mid-evening maximum value. The minimum difference occurred around noon. It is of importance to note that, in the case of December, averaging of the differences at maximum and minimum temperature time to give a mean difference constitutes a poor representation of reality. The difference for minimum temperatures alone would be more representative of the mean.

Data on the horizontal distribution of temperature over Edmonton are limited. Daniels (1965) has produced some isotherm charts, four of which are shown in Fig. III-13 to Fig. III-16. As would be expected, the maximum warmth generally occurred near the central business district. The mean temperature given by Daniels for the city as a whole (the mean of about 200 observations) generally corresponded closely to the actual value at the airport observing site. If these data are representative, they indicate that, although the magnitude of the difference at the airport is only roughly half of the maximum value, it is approximately representative of the city generally.

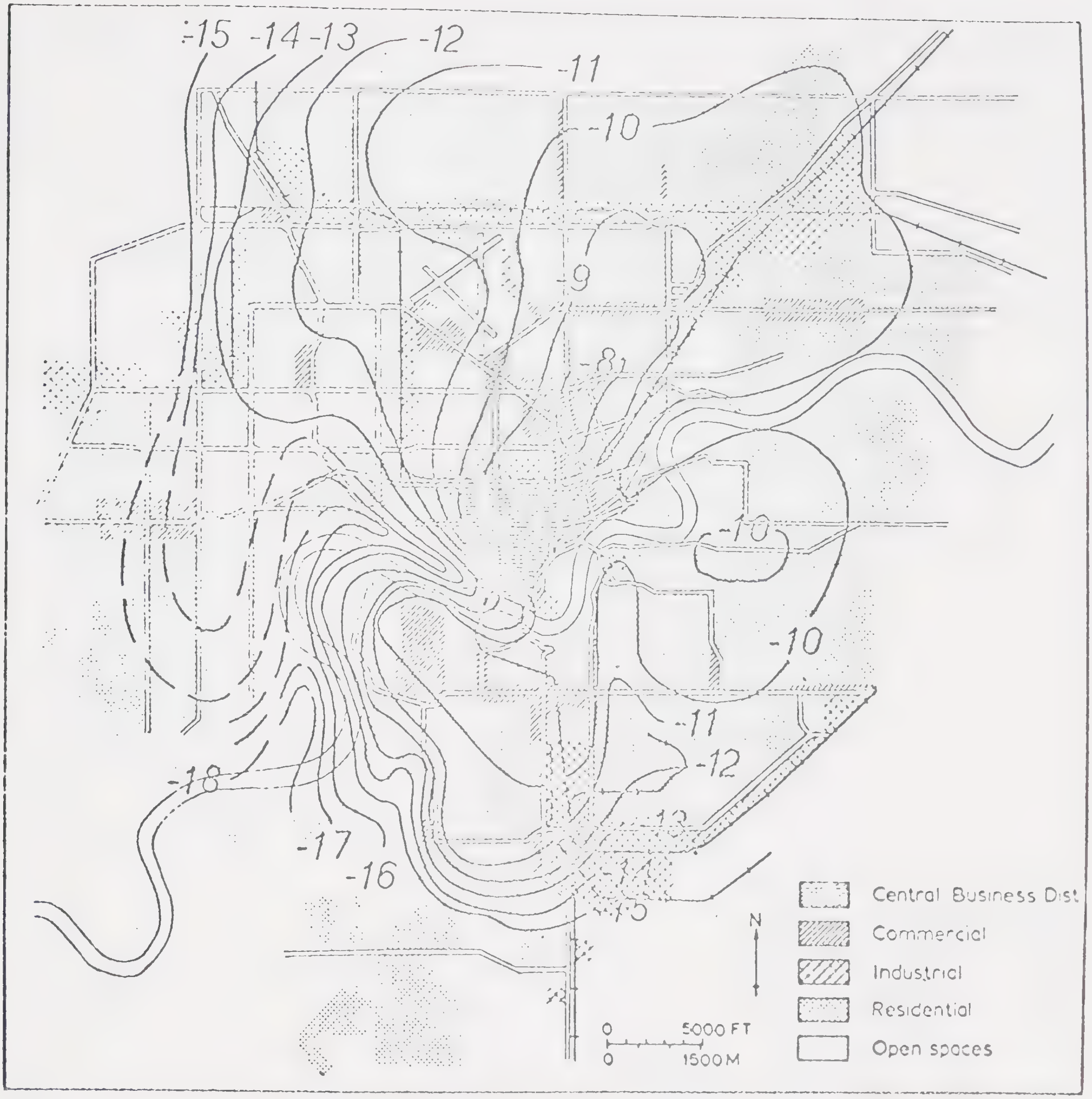

Fig. III-13. Isotherm map for February 12, 1964, around 0300 hrs. (Temperatures in °C). Source: Daniels (1965).

Wind: S, 6.5 m.p.h.
Cloudiness: 0

Mean temperature: -10.8°C
Snow depth: 13 cm.

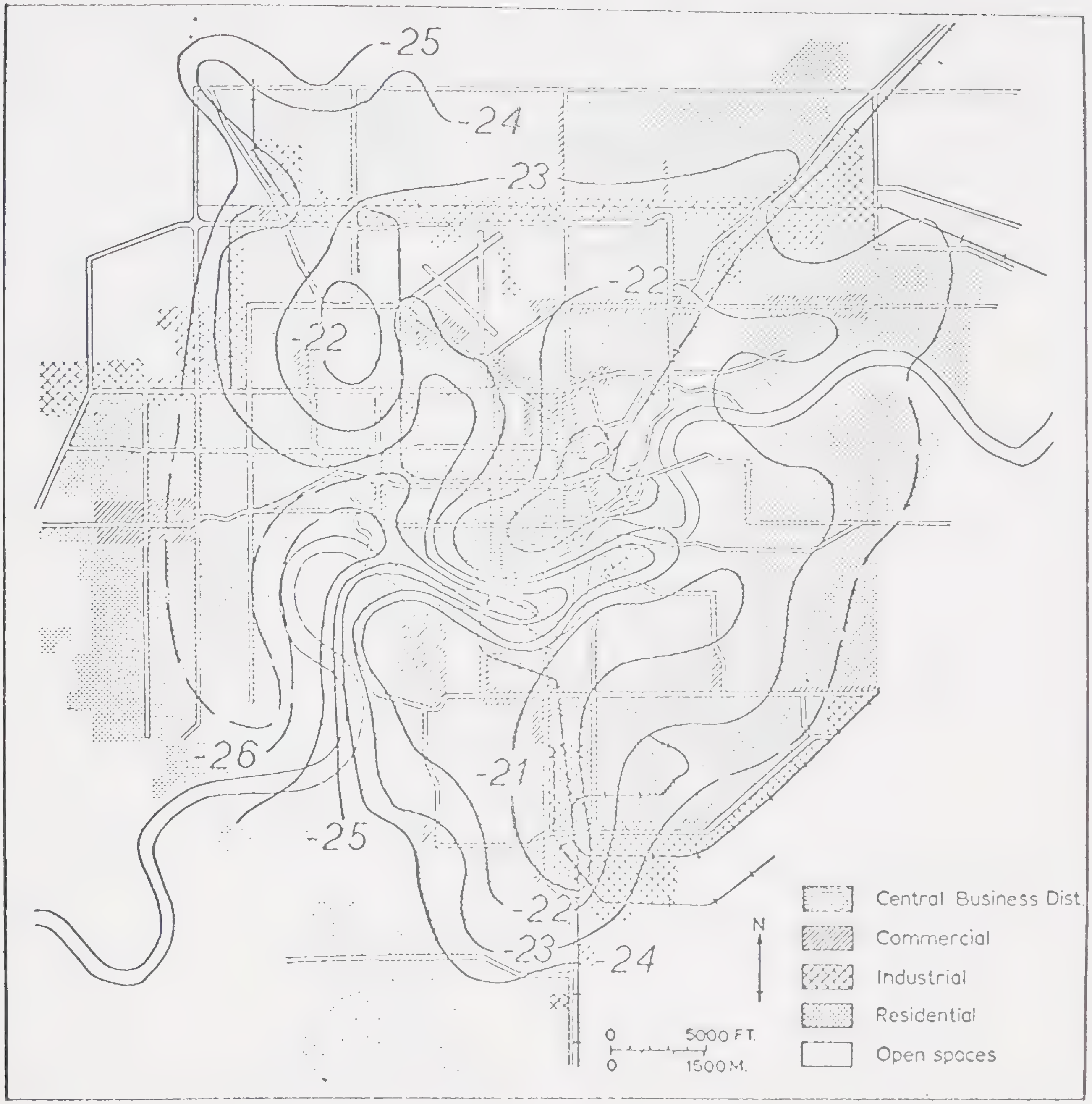

Fig. III-14 - Isotherm map for March 22, 1964, around 2300 hrs. (Temperatures in °C). Source: Daniels (1965).

Wind: N, 8.0 m.p.h. Mean temperature: -22.7°C
Cloudiness: 0 Snow depth: 8 cm.

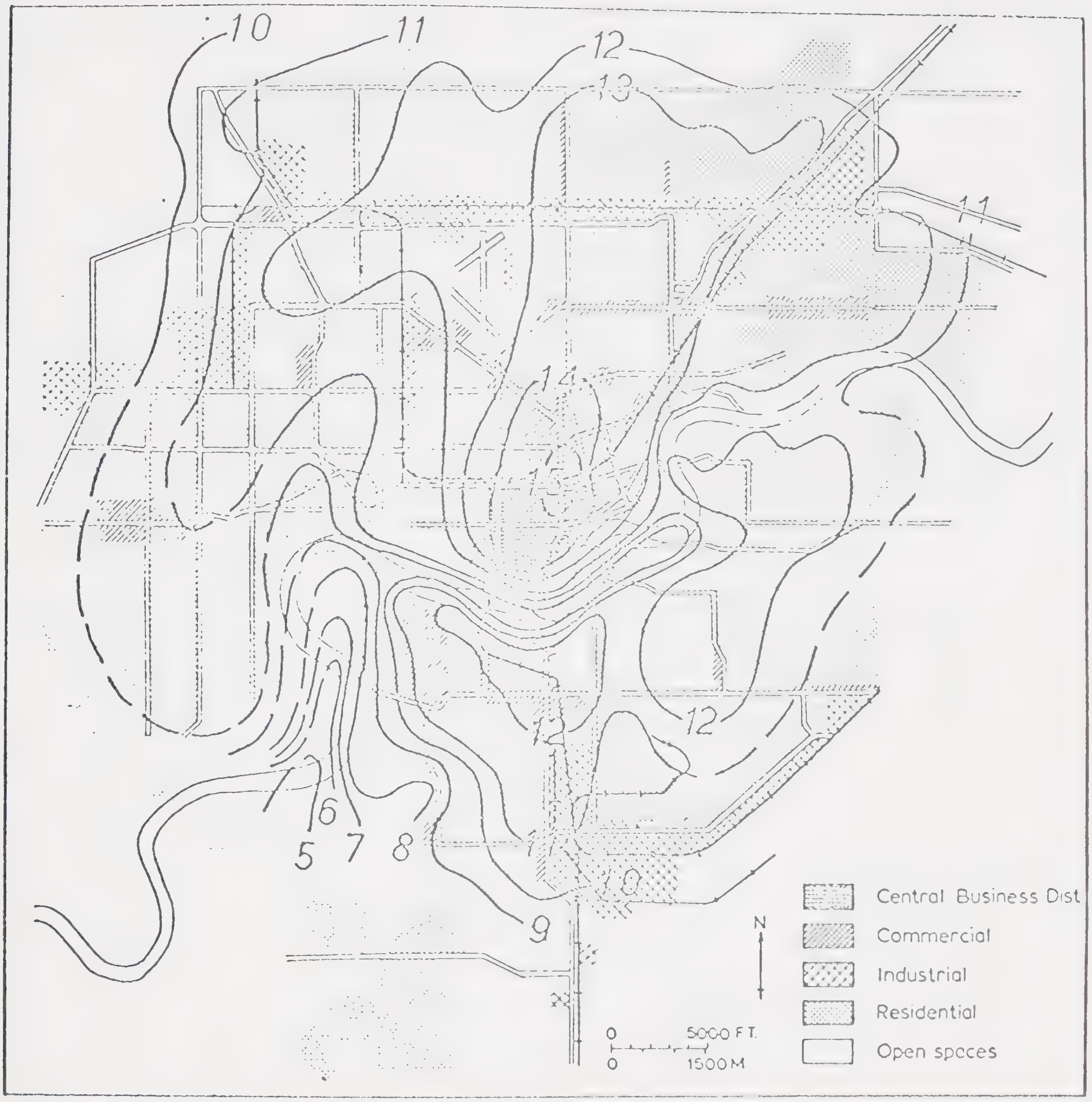

Fig. III-15. Isotherm map for June 10, 1964, around 0200 hrs. (Temperatures in °C). Source: Daniels (1965).

Wind: S, 4.5 m.p.h.
Cloudiness: Ac, 2/10

Snow depth: 0
Mean temperature: 11.7°C

Fig. III-16. Isotherm map for July 21, 1964, around 0300 hrs. (Temperatures in °C.) Source: Daniels (1965).

Wind: S, 7.5 mph
Cloudiness: Ac, 5/10

Mean temperature 14.1°C
Snow depth: 0

CHAPTER IV

EVALUATION AND PROCESSING OF DATA

Change in the Edmonton Observing Site

The previously-mentioned transfer of the Edmonton observing site to the airport in the late 1930s produced significant changes in the temperatures recorded. Fortunately, these changes could be assessed because a period of overlap occurred prior to the closing of the original station. Fig. IV-1 shows differences as a function of the older station temperatures, both maximum and minimum. The values in brackets indicate the number of observations from which each point was computed. The upper curve (maximum temperatures) indicates that the old station was relatively warmer in warm weather, and that the airport was warmer in cold weather. The maximum difference was about $\bar{1}$°F. It is difficult to explain this relationship between the two stations without entering the realm of speculation. The minimum temperature curve generally shows that the airport became increasingly cold relative to the older station as temperatures became lower. As temperatures decreased below 0°F, airport-old station difference rapidly became more negative, reaching a value of about -3.5°F at -26°F.

To make the earlier data as compatible as possible with that of the airport, a least-squares approximation was used to produce polynomials fitting the curves given in Fig. IV-1. These polynomials are represented as broken lines in the diagram. Letting T(XD) represent the airport temperature, and T(XD1) the older station temperature, the mathematical

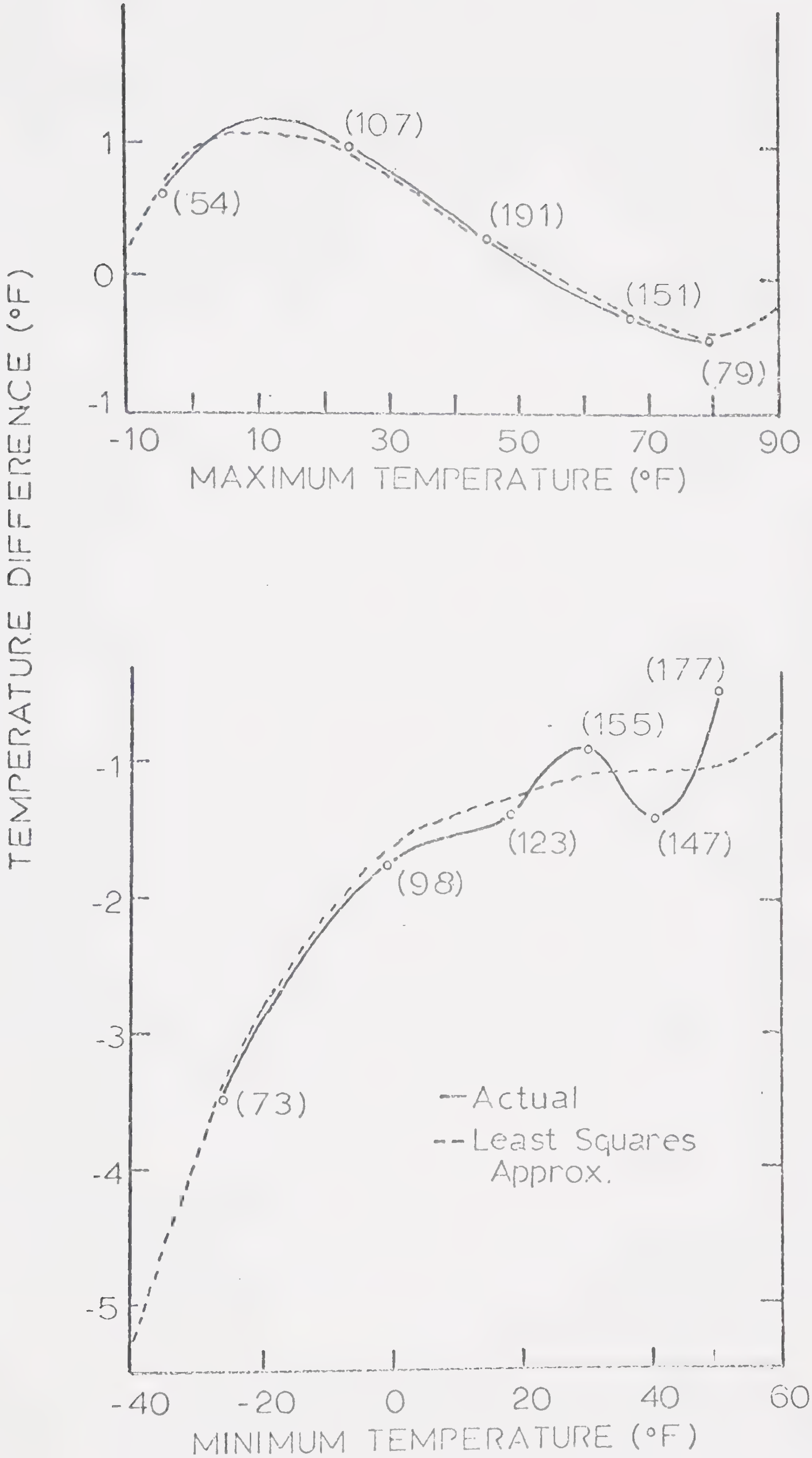

Fig. IV-1. Temperature difference between Airport and Old Station as a function of Old Station temperature.

representation of the curves was, for maximum temperatures:

$$T(XD) - T(XD1) = .113\times10^{-4}T(XD)^3 - .156\times10^{-2}T(XD)^2 + .0371T(XD1) + .822$$

and for the minimum temperatures:

$$T(XD) - T(XD1) = .958\times10^{-5}T(XD1)^3 - .965\times10^{-3}T(XD1)^2 + .0376T(XD1) - 1.69$$

All Edmonton temperatures prior to October 1, 1937, used for comparison purposes in this thesis were adjusted by these equations.

It is desirable to have additional verification of the relationships represented by the least-squares approximations. This is particularly true for minimum temperatures in view of the fairly rapid change in difference exhibited at lower temperatures, and the somewhat erratic nature of the original data for temperatures above 20°F. It must additionally be borne in mind that, for extremes of temperature (both high and low), the approximating polynomials are, of necessity, an extension or extrapolation beyond the available data.

Direct verification of the least-squares approximations is not possible. Perhaps the best approach is to compare Edmonton temperatures with those of another station. Such comparisons are made in the next chapter; hence further discussion of this matter will be postponed.

Data Form and Processing

Temperature and precipitation data used in this and subsequent chapters were for the most part obtained from "Number Four Climatological Cards" provided by the Meteorological Service of Canada. These cards contain daily climatological summaries. Many of them are suitable for machine processing. An IBM 360/67 was used for most computational work. Data used were generally for the period 1929-65, with occasional extensions to 1967.

Classification of Data

In addition to the division of data into maximum and minimum temperatures, two other classifications were extensively used. The first was division into months, in the expectation that urban effects will undergo considerable seasonal variation. A particular month can, however, vary greatly in weather from one year to the next. In order to minimize this variation to some extent, observations were additionally classified in terms of the prevailing rural temperature (at Calmar). Six temperature ranges, listed in Table IV-1, were used for this classification. It is to be noted that the limits of the ranges differ in

TABLE IV-1 - RANGES USED FOR MAXIMUM TEMPERATURE (X) AND MINIMUM TEMPERATURE (N) CLASSIFICATIONS

	Calmar temperature (°F)		Number of observations							
			1950		1951		1952		1953	
Range	X	N	X	N	X	N	X	N	X	N
1	<10	<-15	42	51	37	44	18	21	10	14
2	10 to 29	-15 to 9	71	59	79	73	71	60	59	41
3	30 to 44	10 to 24	63	72	58	62	61	61	78	101
4	45 to 59	25 to 34	69	48	48	48	57	63	80	61
5	60 to 69	35 to 44	58	44	87	69	88	70	75	76
6	>69	>44	62	91	56	69	71	91	63	72

the case of maximum and minimum values. Also given in Table IV-1 is the distribution of the number of days in each range for a typical four-year period. From these latter figures it can be seen that the number of days were, roughly speaking, evenly distributed among the ranges. The exception to this was Range 1, which contained a smaller number of days. These were days upon which temperatures were very low--less than 10°F for maximum temperatures, and less than -15°F for minimum values.

This division of temperatures into ranges effectively minimizes the direct influence of year-to-year temperature fluctuations, and hence of other closely-related phenomena such as space heating. The exception is Range 1 where, by virtue of its lack of any lower limit, yearly temperature fluctuations were large. The warmest range, Range 6, is also "open ended." However, at these temperatures, yearly fluctuations were small. Excluding Range 1, the largest variation of the mean temperature of any range was about 4°F over the 37 years of records.

Latitude and Elevation Effects

The fact that the two stations (Wetaskiwin and Calmar) used for comparison with Edmonton were at significantly different elevations and latitudes than the city resulted in a number of difficulties. One of these was the fact that a single-period comparison between Edmonton temperatures and temperatures at either of the other stations was bound to reflect these differences in location, as well as urban influences. Although this problem can be largely avoided by considering time changes in temperature, it is still useful to estimate mean magnitudes of these non-urban factors. Differences resulting from latitude were computed

TABLE IV-2 - ESTIMATE OF THE INFLUENCE OF LATITUDE AND ELEVATION ON STATION TEMPERATURE DIFFERENCES

	Temperature Difference (°F)					
	Edmonton-Wetaskiwin			Edmonton-Calmar		
Month	lat.	elev.	tot.	lat.	elev.	tot.
Jan	-1.8	-1.6	-3.4	-1.0	-1.0	-2.0
May	-1.4	1.5	0.1	-0.7	0.9	0.2
Jul	-0.7	1.0	0.3	-0.4	0.7	0.3
Oct	-1.0	0.0	-1.0	-0.5	0.0	-0.5

from values given by Haurwitz and Austin (1944) for temperature variations over a flat surface for Alberta. Differences resulting from elevation were calculated from mean vertical temperature gradient data (see Table III-3, Chapter III). Both these sets of differences should only be considered as rough estimates--they are not used in any of the subsequent computations. It is apparent that there is considerable seasonal variation in these values, especially in the case of Wetaskiwin, which varies from more than 3°F warmer than Edmonton in January, to about 0.3°F cooler in October. Because Calmar is closer to the city, both in terms of latitude and elevation, the differences are smaller. It is worth noting that, in winter, elevation and latitude factors complement each other, while in spring and summer they are opposite in sign, tending to nearly cancel in the case of Wetaskiwin.

Comparative Study of Wetaskiwin and Calmar

Before proceeding with a discussion of Edmonton's temperature in relation to Wetaskiwin and Calmar, it is necessary to check for consistency in the values of the latter two stations. Fig. IV-2, Fig. IV-3, and Fig. IV-4 show the differences between Wetaskiwin and Calmar temperatures by year, for both maximum and minimum values. Five-year running means[1] were used for values given by temperature range. There are several marked exceptions to what were generally consistent data. The first entails a distinct decrease in the maximum temperature differences in the 1940s. A similar decrease in the minimum values occurred in the late 1940s and the 1950s. Reference to Fig. IV-4 indicates that this mean decline in the Wetaskiwin-Calmar difference is not apparent for all temperatures. Indeed, for Range 6 of the minima, the trend was reversed, with the difference gradually increasing, for a total change of about 0.8°F over the period of record. For Range 1 of the maximum temperatures, there was

[1]All five-year running means used in this thesis are plotted against the third year.

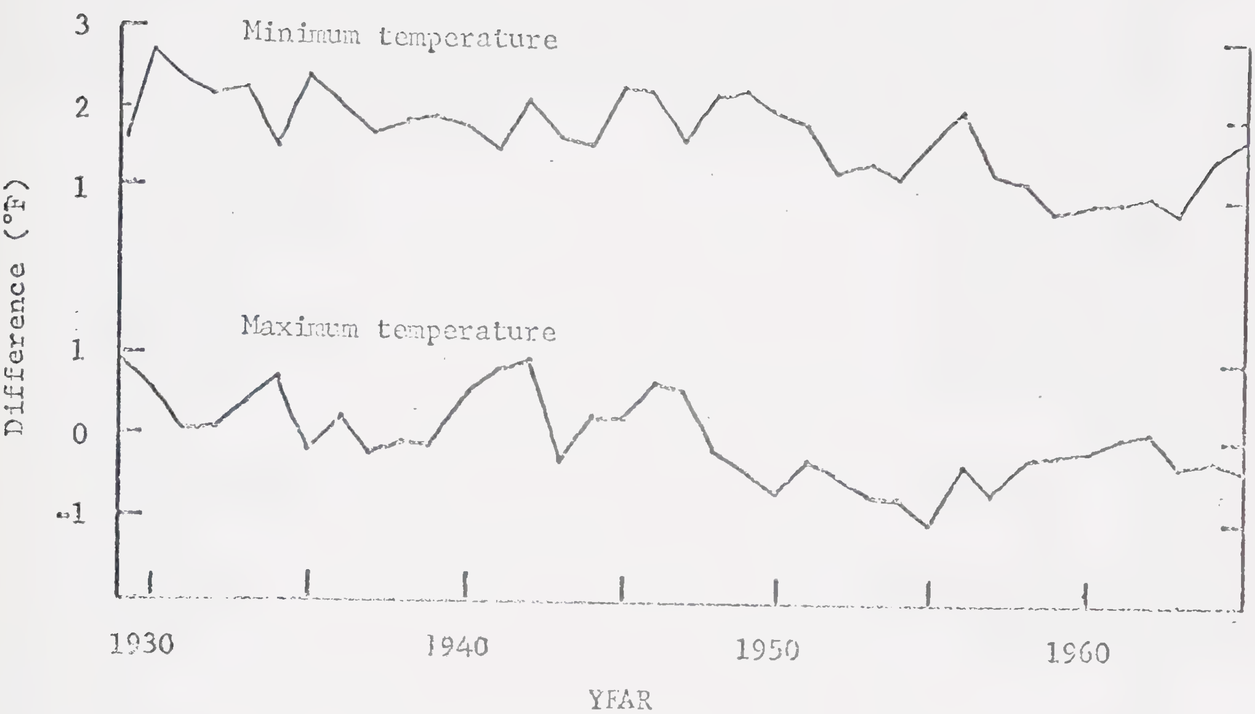

Fig IV-2. Yearly mean differences in temperature between Wetaskiwin and Calmar.

additionally an abrupt change in the differences around 1960.

Fig. IV-5 shows the mean change in the Wetaskiwin-Calmar temperature difference from the period 1931-40 to 1956-65. Changes are given as a function of Calmar temperatures and by month, for maximum and minimum values. For the minimum values, below the freezing point there was a decrease in the differences. This decrease became larger with decreasing temperature. Above the freezing point, the change rapidly increased in value, with positive values for temperatures above about 40°F. On a monthly basis, July and August were alone in showing an increase in Wetaskiwin-Calmar differences. The largest decrease occurred in January.

The situation was somewhat more complex for maximum temperatures. Roughly speaking, however, there was an increase in differences at temperatures of less than 8°F. Above this value, the differences decreased. On a monthly basis, there was a roughly constant decrease,

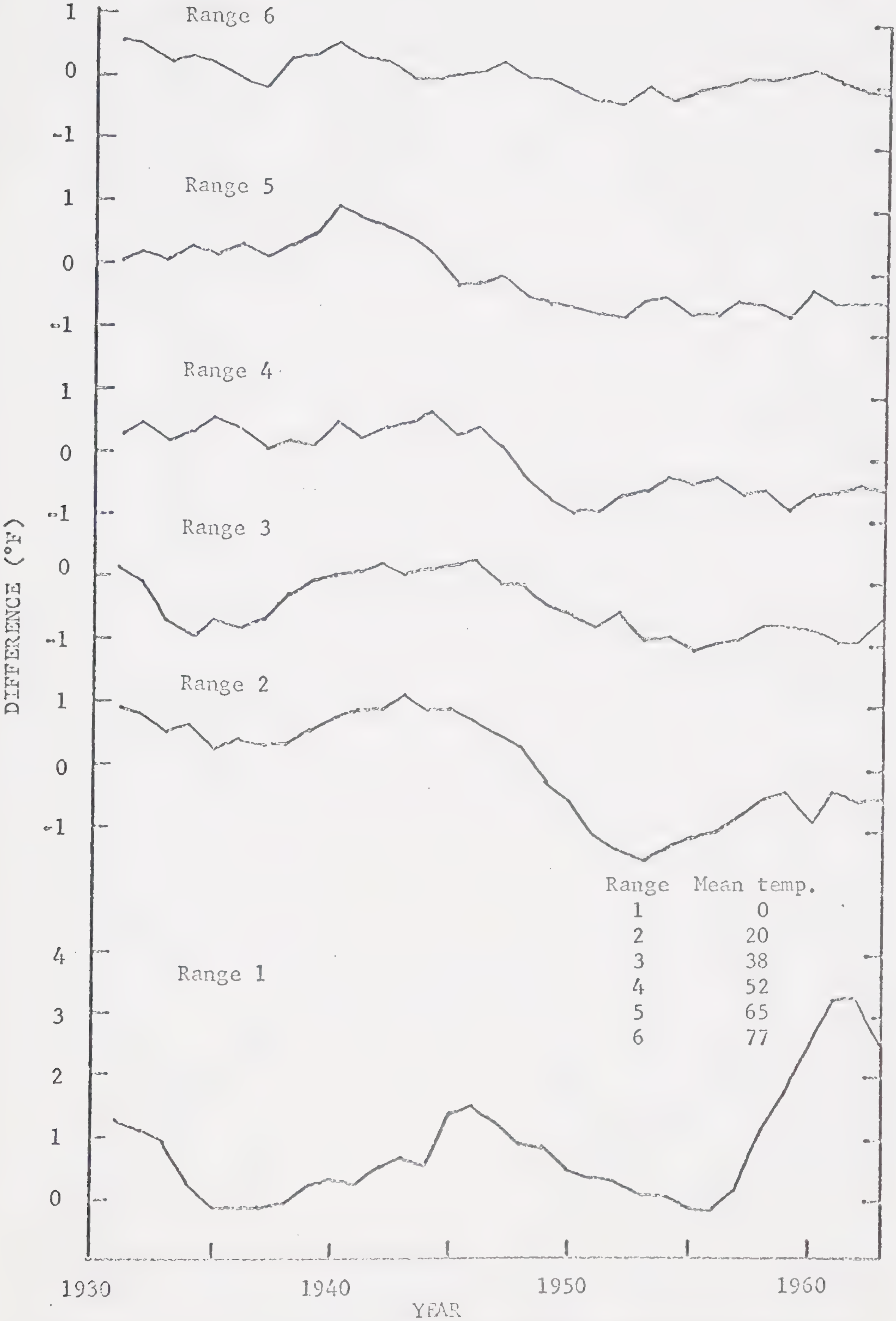

Fig. IV-3. Five-year running means of Wetaskiwin-Calmar maximum temperature difference by range.

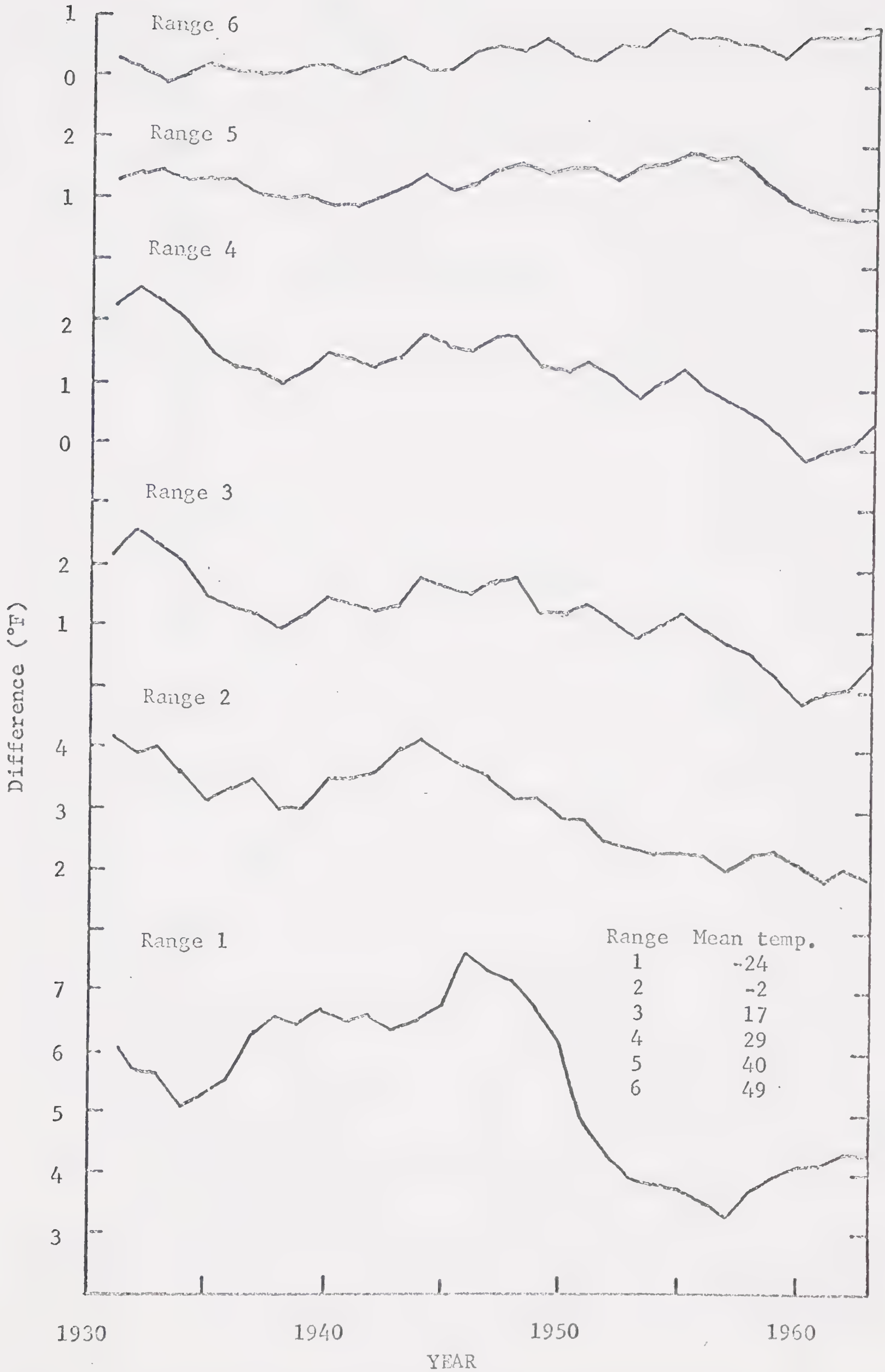

Fig. IV-4. Five-year running means of Wetaskiwin-Calmar minimum temperature difference by range.

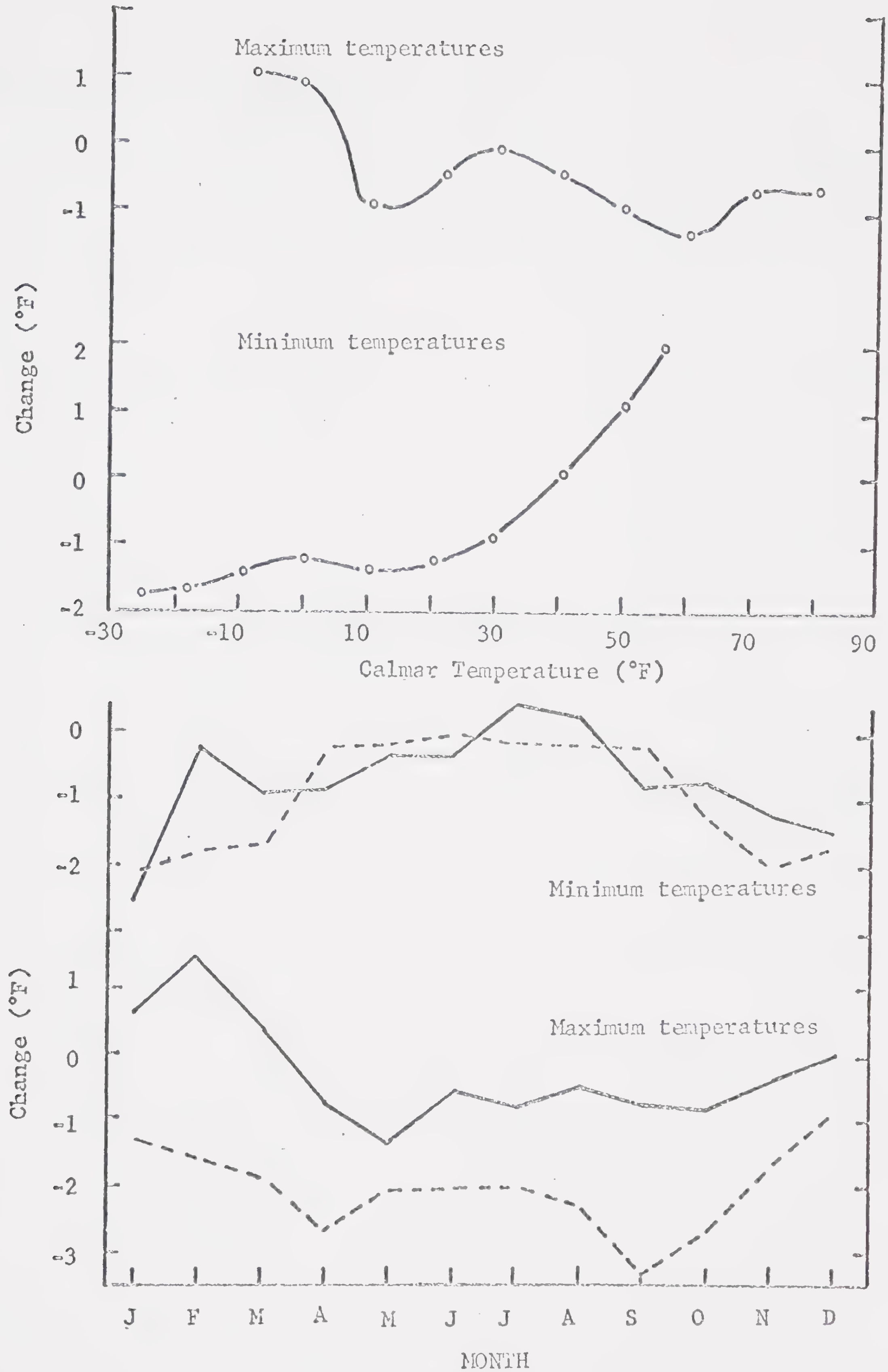

Fig. IV-5. Change in the Wetaskiwin-Calmar temperature difference from the period 1931-40 to the period 1956-65. Broken lines represent an estimate of the effect of a change in observing times.

except for the four winter months.

In summary it appears, therefore, that Calmar warmed (or Wetaskiwin cooled) except for low temperatures in the case of maximum values and high temperatures in the case of minimum values, where the reverse effect occurred.

To study further the nature of this change in the relative Wetaskiwin-Calmar temperatures, comparison was made with a third rural station. Since the Calmar observations were suspect, a location as close to this station as possible was desired. Consequently, Thorsby, lying 9 miles southwest of Calmar, with a population of 600, was chosen. Fig. IV-6 shows Wetaskiwin-Calmar and Thorsby-Calmar yearly minimum temperature differences. Division is into the previously-defined ranges. The time period was limited by the data available. Fortunately, however, it coincided with the period of decline in the minimum temperature differences. Where the downward trend is discernible, it is apparent that the two curves are approximately parallel. The implication is, therefore, that Calmar warmed as opposed to Wetaskiwin cooling, especially in view of the close proximity of Thorsby to the former station.

The increase in the differences for minimum temperatures in warm weather appeared to be much more gradual in nature, extending from about 1940 to the late 1950s. This trend is indicated most clearly in Fig. IV-7, which gives yearly values of the Wetaskiwin-Calmar temperature difference for Range 6 (mean temp. about 50°F). The equivalent Wetaskiwin-Thorsby curve included in the figure failed to reveal any such trend, again indicating that the cause of the change in the difference rested with Calmar. In other words, in warm weather, Calmar's minimum temperatures, relatively speaking, cooled between 1940 and 1960.

Fig. IV-8 illustrates the change in the Wetaskiwin-Calmar and

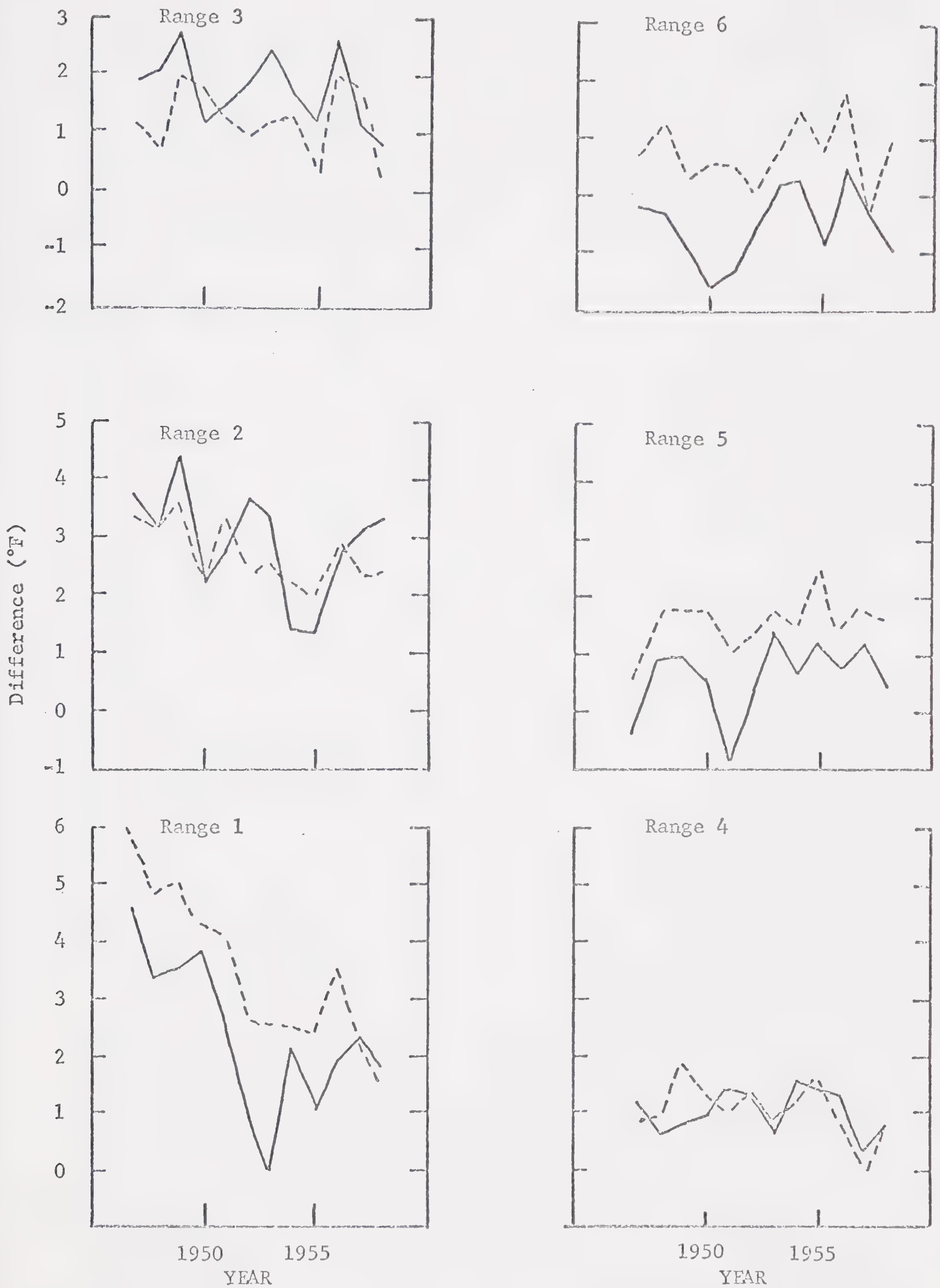

Fig. IV-6. Wetaskiwin-Calmar (solid lines) and Thorsby-Calmar (broken lines) minimum temperature differences by range.

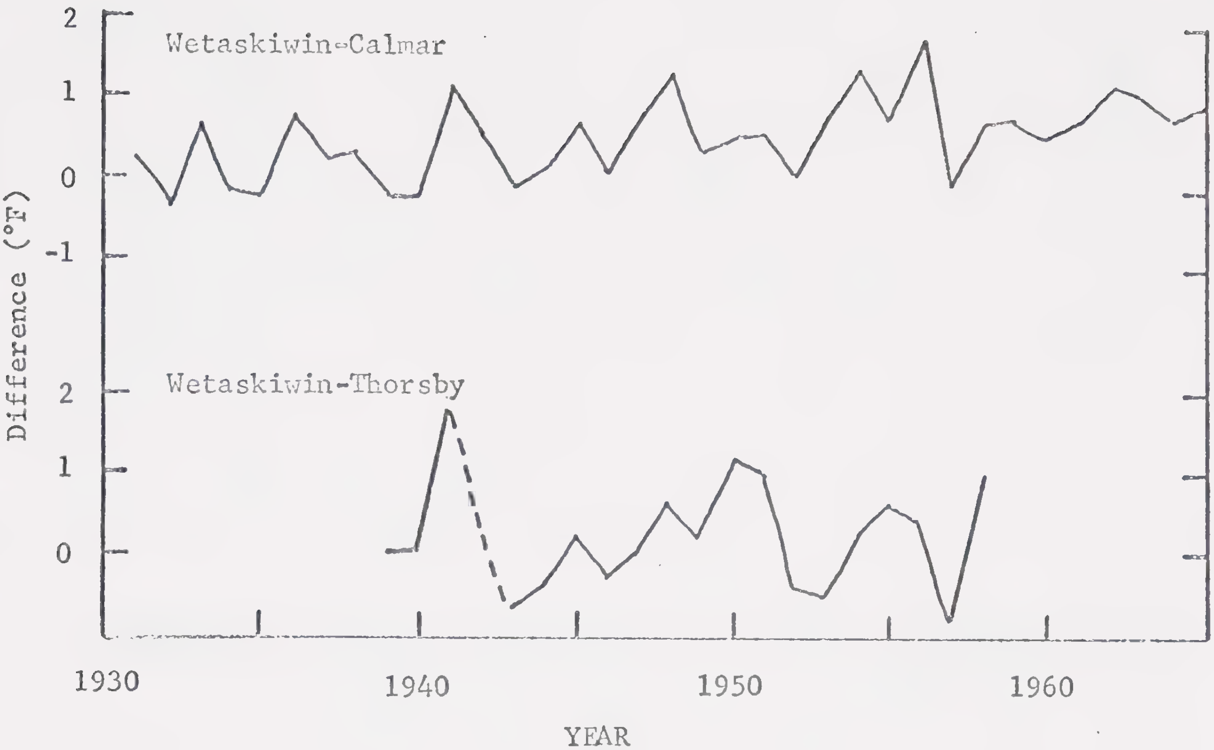

Fig. IV-7 - Mean minimum temperature differences between Wetaskiwin, Thorsby, and Calmar, for Range 6.

Thorsby-Calmar differences for maximum temperatures. The change is from the period 1938-41 to the period 1954-55 plus 1957-58. Except for the anomaly in July, this figure again illustrates that the decrease in the Wetaskiwin-Calmar difference was also present in the Thorsby-Calmar difference. Apparently, in this case, Calmar had also warmed relative to the other two stations.

For maximum temperatures, January, February, and March showed an increase in the Wetaskiwin-Calmar difference, as indicated in Fig. IV-5. This increase resulted from the large differences occurring in Range 1 around 1960 (see Fig. IV-3). A detailed look at the data indicates that some very low Calmar temperatures in cold weather caused the increase. The low values occurred in the period 1959-61, especially 1960.

From the above discussion it appears that Wetaskiwin is a considerably more reliable station for comparison purposes than Calmar. This is

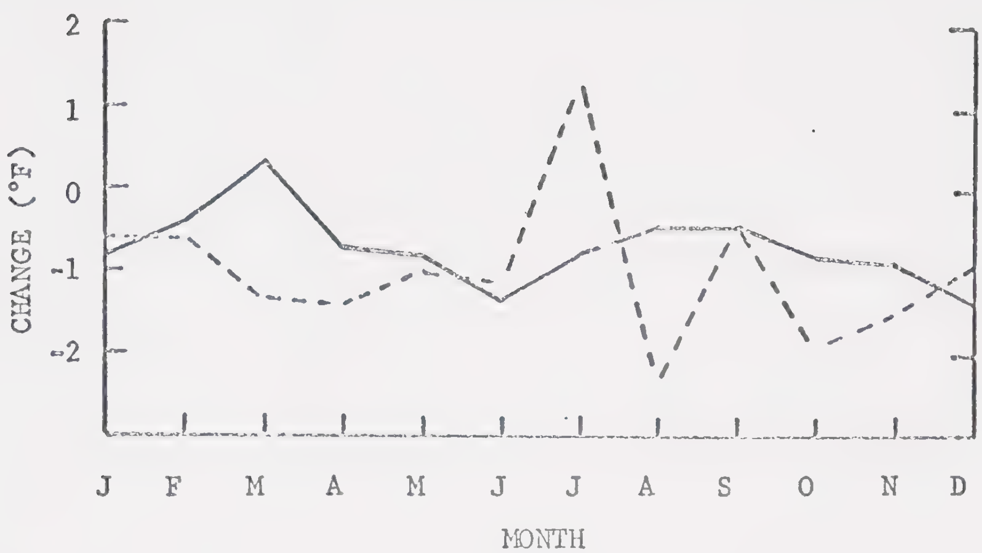

Fig. IV-8. Change in the Wetaskiwin-Calmar (solid line) and Thorsby-Calmar (broken line) maximum temperature differences frmm the period 1938-41 to the period 1954-55, 1957-58.

unfortunate for two reasons. First, the fact that Wetaskiwin is at a considerably different elevation and latitude than Edmonton means that, on a short-term basis, temperature differences between the two sites will be dependent to a considerable extent on the particular synoptic situation. For example, stability and north-south temperature differences will have a considerable, and varying, influence. The difficulties arising from this fact will be discussed further in subsequent chapters. The second drawback to Wetaskiwin is the fact that it does not represent a truly rural site. Not only is it surrounded by a small urban area, but the size of this area has grown, in terms of population, from about two thousand to about six thousand over the period of interest. Although the associated urban influences are probably small, they may not be insignificant under all circumstances.

It would be desirable to discover some reason for the apparent peculiarities in Calmar data. After examination of the observing sites

and conversation with the people involved, it became apparent that this reason was somewhat elusive. The only noteworthy fact to be uncovered was that, while at Wetaskiwin the observations were taken daily at 8:00 a.m. and 8:00 p.m., at Calmar a single observation was taken at 8:00 p.m. In itself, this fact would not explain a change in the difference between the temperatures recorded at the two stations. A change would certainly be expected to occur with a change in the time of Calmar's readings, however. The Calmar observer stated he had no recollection of such a change. It is of interest to note that, as can be seen from Fig. IV-2, the pronounced drop in the Wetaskiwin-Calmar maximum temperature differences in 1947 coincided with the time at which there was a change of observers at the station. Additionally, Calmar is officially listed as taking an 8:00 a.m. observation, implying perhaps that the time has been changed to the evening without notification.

If the observing time had been changed from 8:00 a.m. to 8:00 p.m., what changes in the temperatures could be expected? Burrows (1964) has studied the effects of different observing times. He could find no significant differences in temperatures derived from twice-daily readings at co-operative stations such as Calmar, and those derived from the observations taken four times daily at principal stations such as Edmonton. For a station taking observations only in the morning, maximum temperatures were found to be unchanged from twice-daily readings, because the maximum thermometer was read daily at the same time in both cases. Similarly, for a station taking observations in the evening only, minimum temperatures were comparable. The recording of maximum temperatures in the evening produced anomalously high values, however. Differences of 1-3°F were typical. On the other hand, recording of min-

imum temperatures in the morning tended to produce anomalously low values. This was especially true in spring, with 3-4°F differences being typical.

Based on Burrow's (fairly typical) data for Vauxhall, Alberta, it was possible to estimate the effects of a change in observing times from 8:00 a.m. to 8:00 p.m. at Calmar on the difference between its temperature and that of Wetaskiwin. This estimate is represented by the broken lines in Fig. IV-5. It can be seen that, in the case of minimum temperatures, this curve fits the observed changes quite well. For the maximum values, the magnitude of the estimated warming at Calmar is considerably larger than actually observed. The difference in the sign in late winter is attributable to the anomalous data from Calmar around 1960.

Conceivably, on the basis of the above discussion, a change in observing times from morning to evening could explain much of the apparent temperature change at Calmar. The fact that Calmar minimum temperatures appeared to increase gradually over a number of years (decrease in the case of very warm weather) is not easily reconciled with a sudden change in observing procedures, however.

In summary then, in spite of the previously-mentioned difficulties, it was found necessary to use Wetaskiwin as the primary standard against which to measure Edmonton temperatures. The difficulties with Calmar may have involved a change in observation times; however, the evidence on this point is not conclusive.

It is to be noted that, in spite of the objections to Calmar's temperatures, the readings from this station have been used for classification purposes. For example, Calmar readings were used to determine into which temperature range (as defined previously) a particular day would be classified. Calmar was chosen for two reasons. First, it was

desired to use temperatures representative of the rural area near Edmonton. The values for Wetaskiwin, as will be seen presently, vary considerably from those near Edmonton, with the magnitude of the variation changing rapidly with temperature. The second reason is somewhat more obscure. Attempts to relate temperature differences between two stations to the temperature, or other closely related parameters, give a particular form of distortion if these latter values are based on temperature readings from either of the two stations involved. It was necessary to compare Edmonton temperatures to those of Wetaskiwin; consequently, data from a third station had to be used to prevent this distortion. Calmar was the only other station for which sufficient data were available. This problem will be discussed in more detail in a subsequent chapter.

CHAPTER V

THE NATURE OF TEMPERATURE CHANGE IN EDMONTON

Time Series of Maximum Temperatures

The differences between Edmonton and Wetaskiwin maximum temperatures for the period 1929-65 (occasionally extended to 1967) are given in Fig. V-1, Fig. V-2, and Fig. V-3. Differences are on a yearly basis, by temperature range, and by month, respectively. The main features of the general pattern can be described briefly. A period of little change in the Edmonton-Wetaskiwin differences was followed by a drop in the late 1930s. From about 1946 to 1956, coincident with the rapid expansion of the city, there was a relatively constant increase in differences. In the mid-fifties another period of decline occurred followed by a period of recovery beginning in the early 1960s. This pattern was generally adhered to on a month-by-month or range-by-range basis. The most notable exceptions were February and March, which showed distinct maxima in the differences in the mid-thirties. For these two months, the earlier minima in the differences were advanced in time somewhat, to about 1946. October stood alone in not showing any decline in the late 1950s. This decline was most pronounced in June, and least pronounced in the fall.

Some measure of the significance of these data may be obtained from statistical tests. The application of a paired t-Test to the yearly values of Edmonton-Wetaskiwin maximum temperature differences indicated that, on the average, a difference of 0.5°F was significant at the 99 per cent level. The vertical bar on the curve of yearly maximum differences (Fig V-1) represents this interval. The relatively small size of

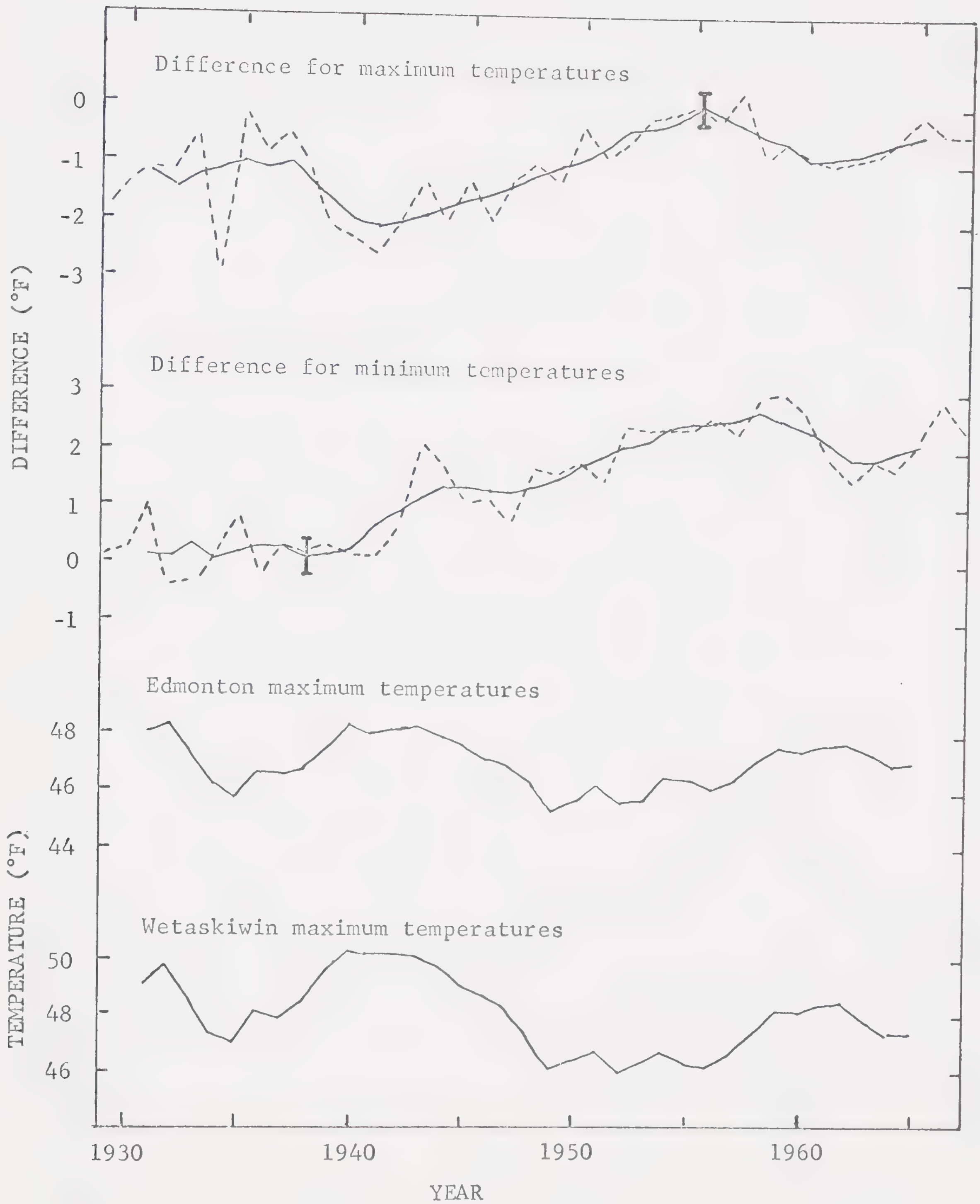

Fig. V-1. Yearly values of Edmonton-Wetaskiwin temperature differences. Edmonton and Wetaskiwin yearly mean maximum temperatures are included. Solid lines are five-year running means.

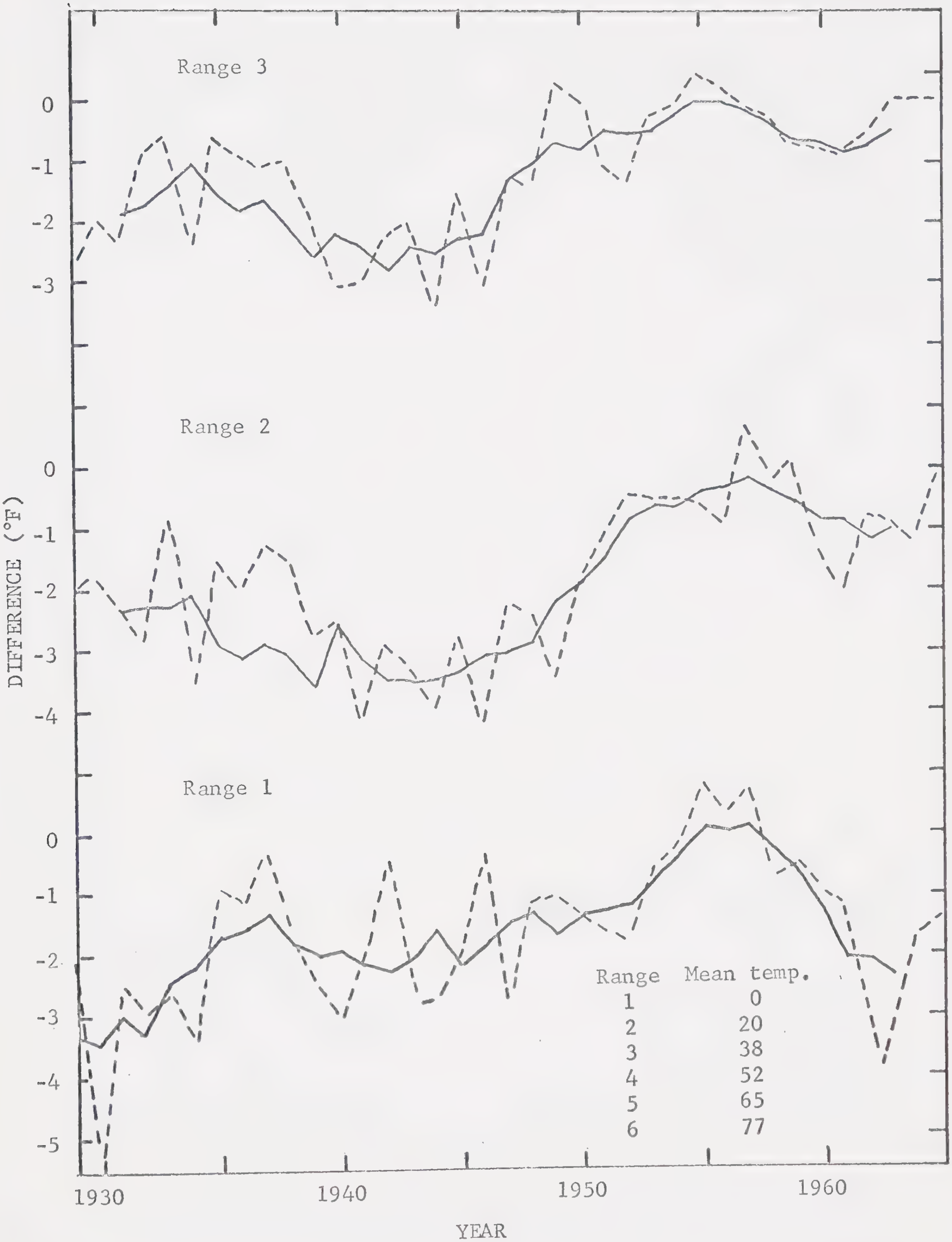

Fig. V-2a. Edmonton-Wetaskiwin maximum temperature differences by range. (Solid lines are five-year running means.)

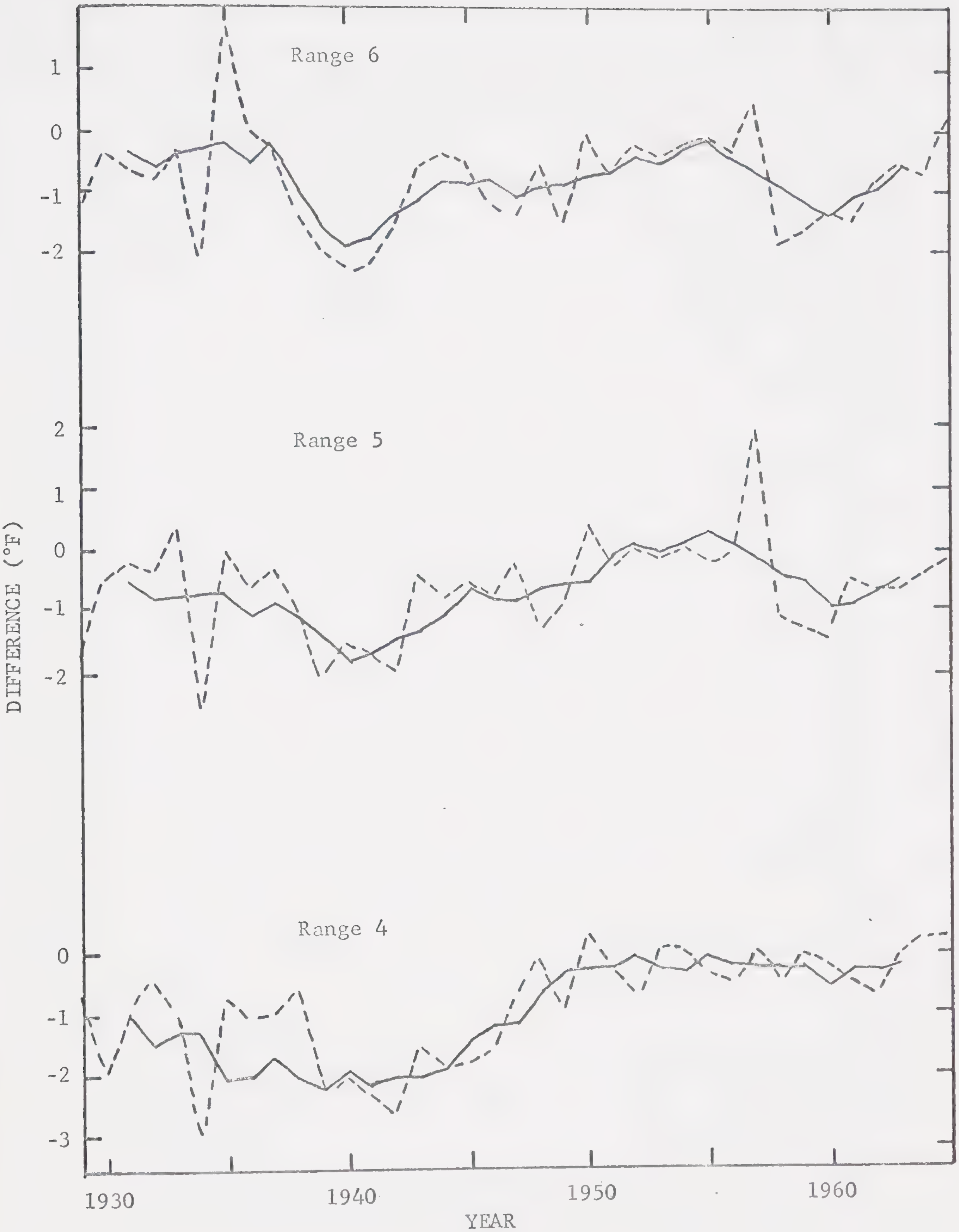

Fig. V-2b. Edmonton-Wetaskiwin maximum temperature differences by range. (Solid lines are five-year running means.)

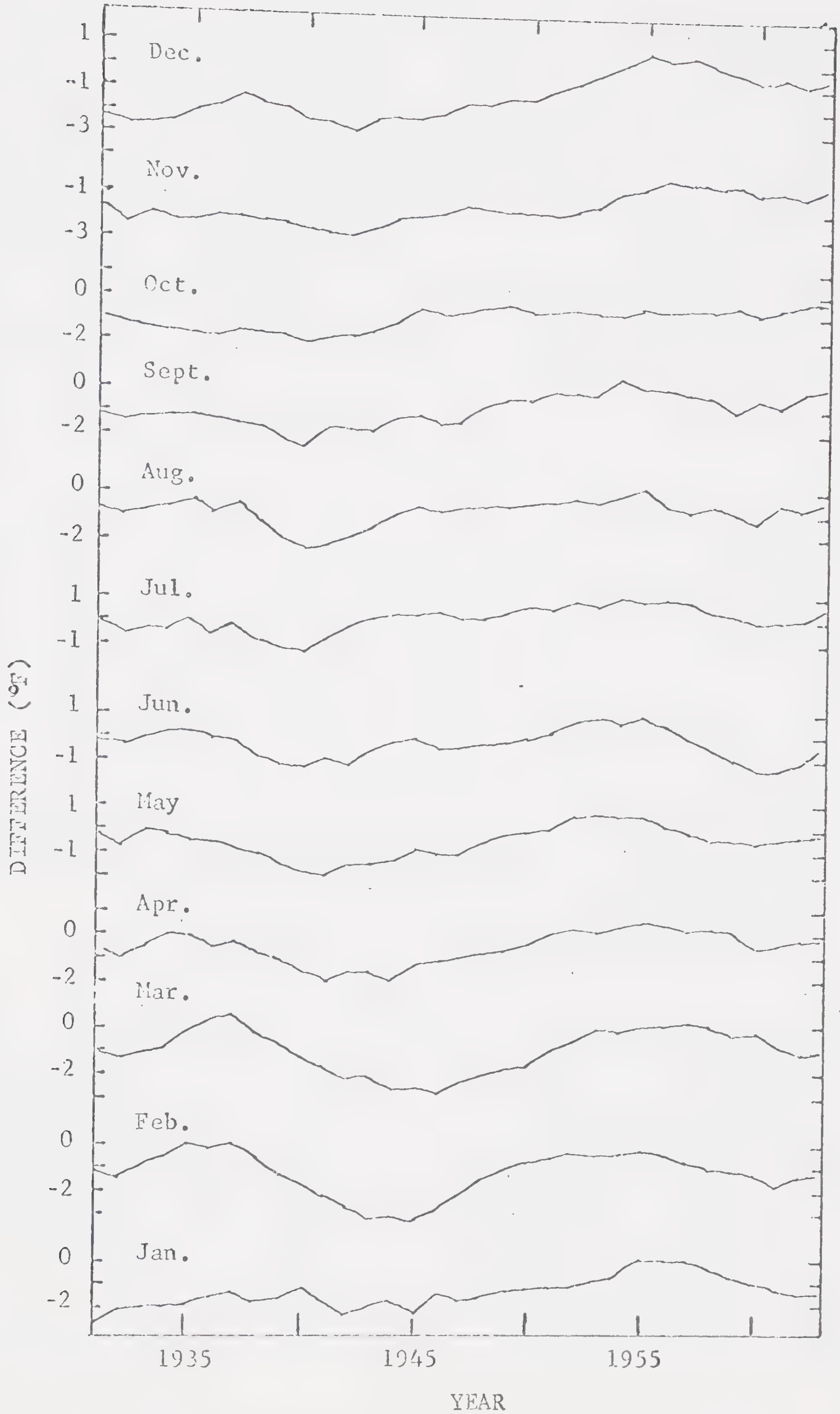

Fig. V-3. Five-year running means of Edmonton-Wetaskiwin maximum temperature differences by month.

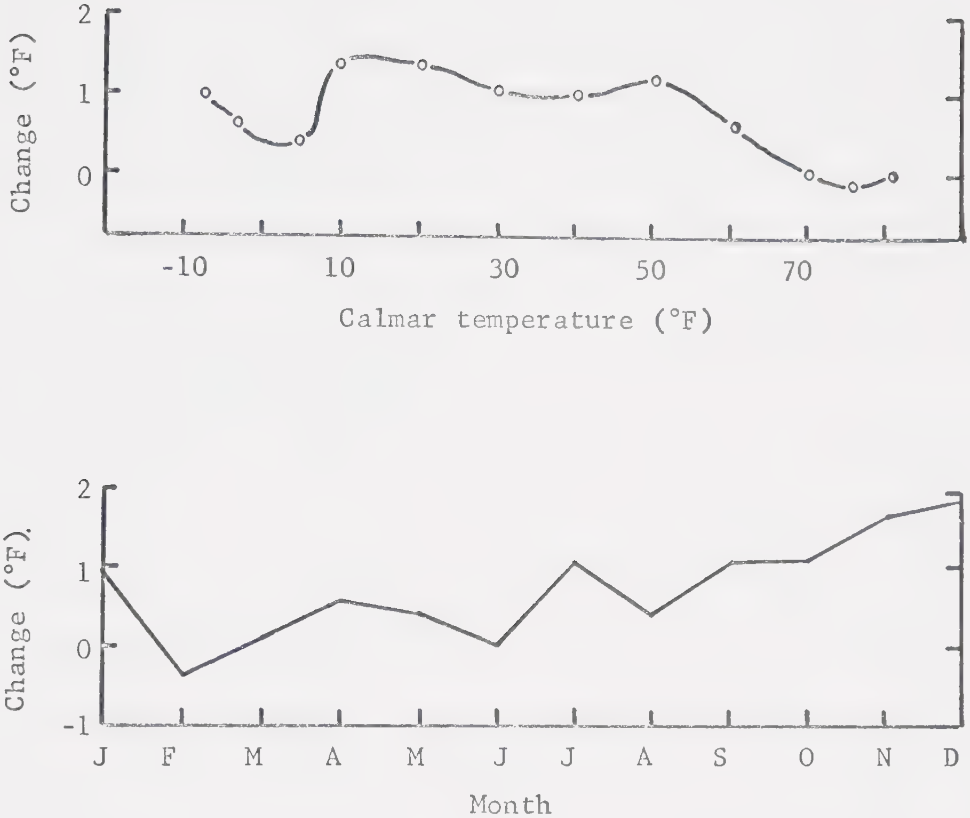

Fig. V-4. Change in the Edmonton-Wetaskiwin temperature difference from the period 1931-40 to the period 1956-65. Values are for maximum temperatures. The lower graph gives the change on a monthly basis. The upper graph gives the change as a function of Calmar maximum temperatures.

this significant difference lends support to the suggestion that, of the fluctuations in this yearly curve, at least the minima around 1940 and 1960 were significant. The 2°F increase in the differences between 1940 and 1955 was large relative to the size of this confidence interval.

Fig. V-4 shows the mean change in the Edmonton-Wetaskiwin maximum temperature difference from the period 1931-40 (mean population 85,000[1])

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[1]The city's 1935 population was used to represent the mean for the 1931-40 period.

to the period 1956-65 (mean population 300,000[1]) as a function of temperature, and on a monthly basis. The apparent warming of Edmonton was least from late winter to late spring. A gradual increase extended through summer and fall to a maximum in December. From Fig. V-4 (upper curve), it can be seen that, excluding the dip around 0°F, the apparent warming of Edmonton was only slightly dependent on temperature below 50°F. Above this temperature, the change in the difference declined to about zero at 70°F.

Time Series of Minimum Temperatures

Figs. V-1, V-6, and V-7 give analogous results for minimum temperatures. In contrast to the maximum values, there was no distinct minimum in the Edmonton-Wetaskiwin differences prior to 1940. An abrupt increase in the yearly mean values (Fig. V-1) occurred about 1943, followed by a decline to about 1946. Coincident with a period of rapid expansion of Edmonton, there was an apparent warming of the city from 1947 to 1959. A period of cooling in the early 1960s was followed by a nearly complete recovery by 1966. It is to be noted that this cooling period occurred about 4 years later than did the one for maximum temperatures.

There was a general consistency to this pattern on a month-to-month or range-by-range basis, although spring and summer months showed weak minima in the 1940s.

The application of a paired t-Test to the yearly values of Edmonton-Wetaskiwin minimum temperature differences indicated that on the average, a difference of 0.5°F was significant at the 99 per cent level. The vertical bar on the curve of yearly minimum differences (Fig. V-I) represents this interval. It is apparent that, in terms of this t-Test, the

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[1]The city's 1960 population was used to represent the mean for the 1956-65 period.

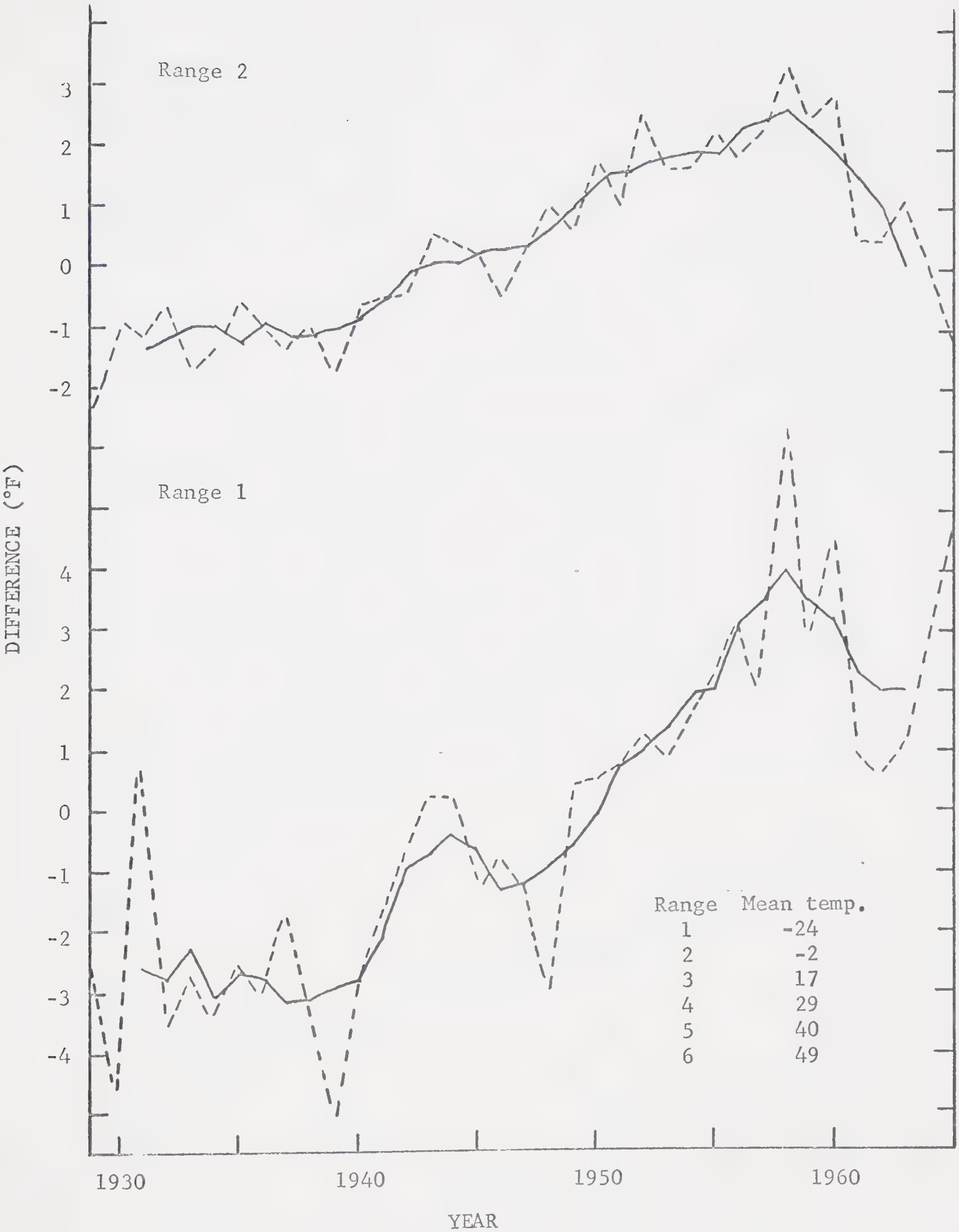


Fig. V-6a. Five-year running means of Edmonton-Wetaskiwin minimum temperature differences by range. (Broken lines are yearly values.)

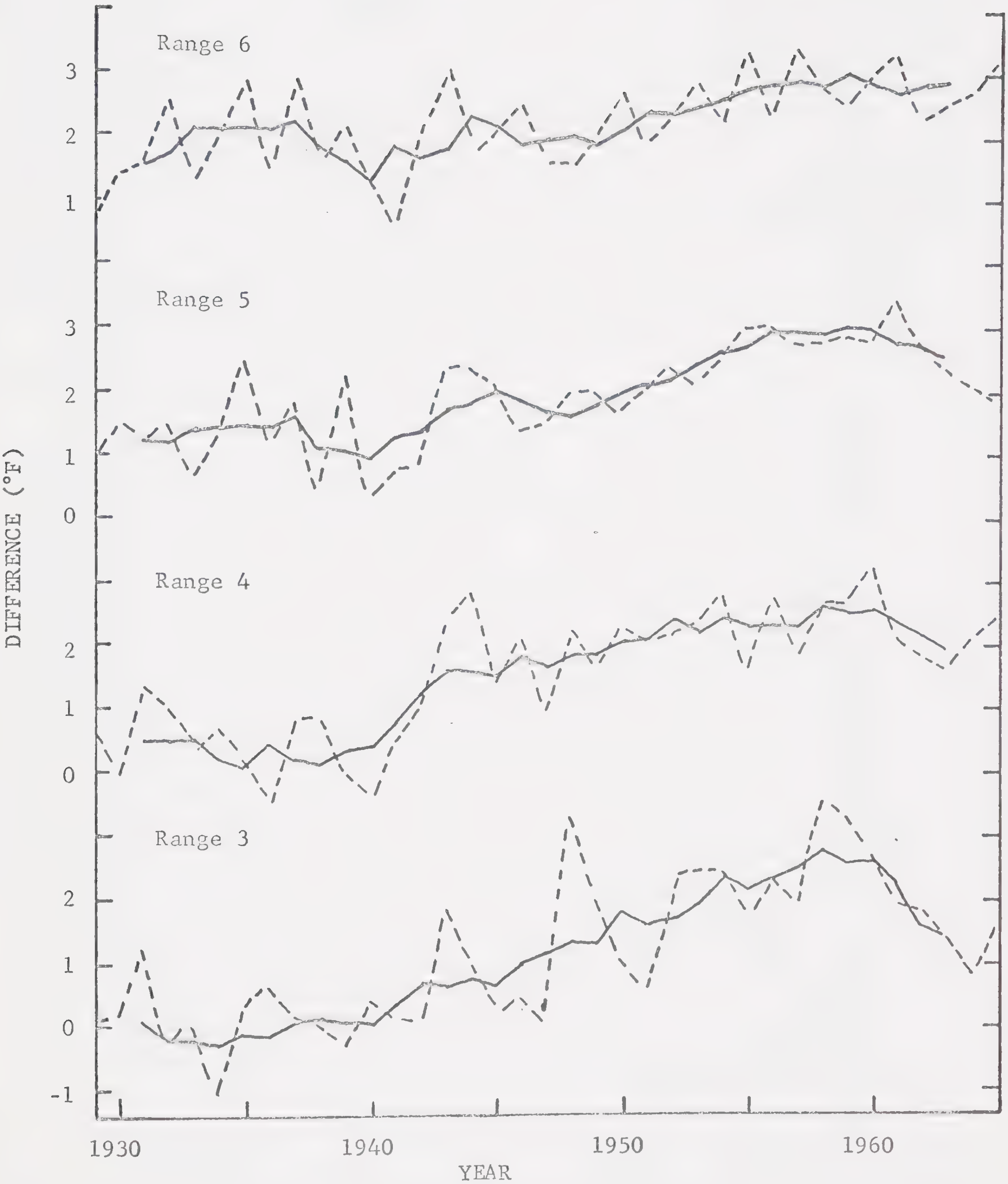


Fig. V-6b. Five-year running means of Edmonton-Wetaskiwin minimum temperature differences by range. Broken lines represent yearly values.

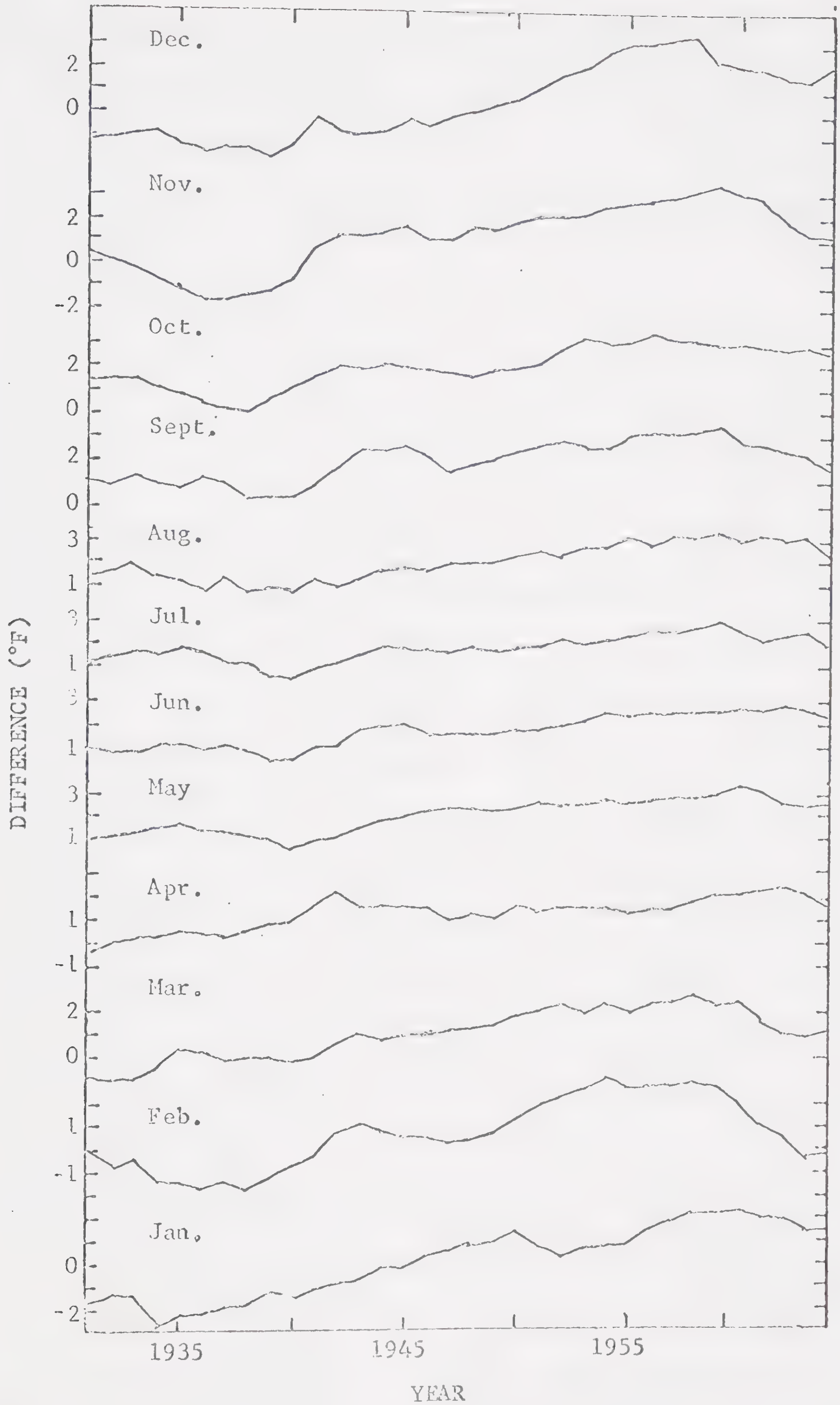


Fig. V-7. Five-year running means of Edmonton-Wetaskiwin minimum temperature differences by month.

declines in differences beginning in 1944 and 1961 were significant, as was the general upward trend that occurred through the late 1940s and 1950s. Other fluctuations could also be considered as significant; however, they were smaller and consequently of lesser importance to the general trend in differences.

Fig. V-8 shows the change in the difference between Edmonton and Wetaskiwin minimum temperatures from the period 1931-40 to 1956-65. At temperatures below 5°F, the apparent warming of Edmonton was strongly dependent on temperature, decreasing from 5.6°F at -26°F to 1.8°F at 5°F. Between 5°F and the freezing point, there was only slight temperature dependence. Above the freezing point, the amount of Edmonton's apparent warming decreased to about zero at 55°F. There are two major differences between this relationship and the equivalent one for maximum temperatures. First, the magnitude of the change was considerably greater in this case. Secondly, the strong temperature dependence exhibited by the minimum values at low temperatures was not apparent in the case of the maximum values. On a monthly basis, Fig. V-8 indicates that the change in the difference was least in July, and greatest in January. The amount of apparent warming was roughly constant at 1.2°F to 1.6°F from April to September. January showed the largest amount of warming, with an increase of 3.6°F.

The Problem of the Edmonton Station Change

As discussed in the preceding chapter, it is desirable to have some verification of the accuracy of the least-squares approximations used to compensate for relocation of the Edmonton observing site. To find such verification is not an easy task. One obvious approach to the problem is to examine the Edmonton-Wetaskiwin differences for the period around 1937 when the transition between stations was made. The primary weakness

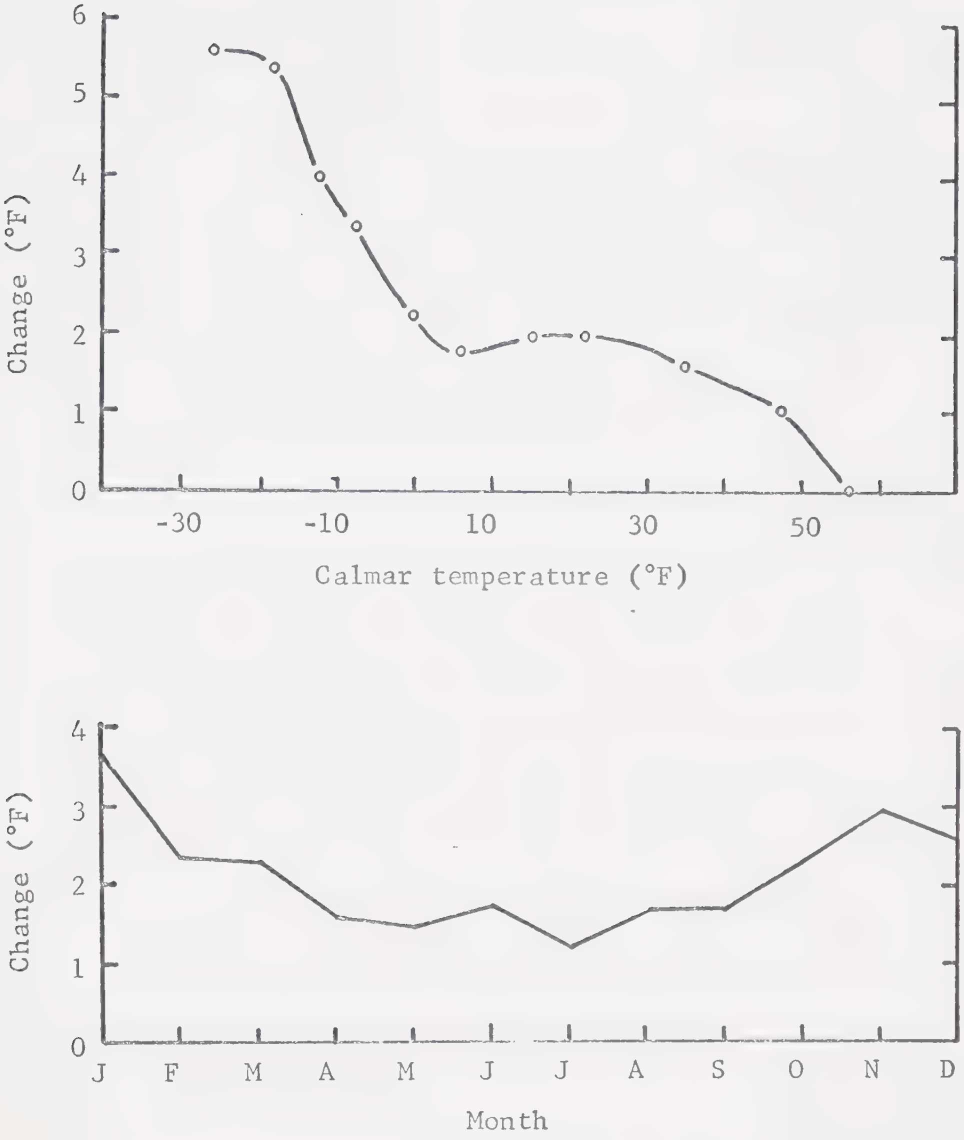


Fig. V-8. Change in the Edmonton-Wetaskiwin temperature differences from the period 1931-40 to the period 1956-65. Values are for minimum temperatures. The lower graph gives changes on a monthly basis. The upper gives changes as a function of Calmar minimum temperatures.

of this approach is that these differences could have been dependent on other factors which cannot readily be isolated. Urban influences are one possible factor to be considered. The considerable difference in location between Edmonton and Wetaskiwin constitutes another potential influence, as previously discussed.

In spite of the above difficulties, it is worthwhile examining the Edmonton-Wetaskiwin temperature differences around 1937 to see if any discontinuities, which could be attributed to the approximations used, actually appeared. The minimum temperatures are of primary concern, because the required adjustments were much larger for these than for maximum temperatures. On a yearly basis, Fig. V-1 indicates little change in the Edmonton-Wetaskiwin minimum temperature differences through the period 1930 to 1941. On a range-by-range basis (Fig. V-6) no discontinuity is noticeable around 1937.

For maximum temperatures, there was little change in the differences between the years 1936 and 1938, as indicated in Fig. V-1 and Fig. V-2. However, there was a tendency for a distinct decrease in differences after 1938. Unfortunately, these difference values showed a distinct negative correlation with maximum temperature. This relation will be discussed in a subsequent chapter. For the time being, it is sufficient to note that the decline in differences after 1938 corresponded to a period of strong warming (see Fig. V-1). Possibly, this decline could be attributed, therefore, to increasing temperature. Consequently, we are left with no clear indication of discrepancies in maximum values caused by the station location change.

In summary, it is apparent that the above discussion lacks the quantitative nature that would be desired. This is unavoidable, however.

If compensation for the change of site led to errors, they are not at all discernable for minimum temperatures. If they occurred for maximum values, other factors have served to mask them.

Functional Relationship between Edmonton and Wetaskiwin Temperatures

In order to examine more closely the relationship between Edmonton and Wetaskiwin temperatures, consider first Fig. V-9 and Fig. V-10, which show the Edmonton-Wetaskiwin difference (as opposed to the previous figures which showed the change in the difference) for the periods 1931-40 and 1956-65. Values are given as a function of temperature and by month, for both maximum and minimum temperatures.

In the 1931-40 period, for minimum values, the Edmonton-Wetaskiwin differences increased rapidly with temperature from -3°F at -30°F, to almost 3°F at 55°F. The primary weakness of this type of temperature relationship is that it groups together spring and fall observations, which may be similar in temperature but quite dissimilar in other ways, such as stability. In this particular case, however, it can be seen that the spring and fall temperature differences were much alike.

It is tempting to explain this relationship in terms of the differences in latitude and elevation of the two stations. Referring back to Table IV-2, which gives the estimated mean temperature differences arising from these two factors, it can be seen that, roughly speaking, the computed magnitude and seasonal trend are in accord with the observed differences. Although latitude and elevation probably contributed to a considerable degree, two observations suggest that other considerations were involved as well. First, an equivalent comparison of Edmonton-Calmar minimum temperature differences showed an almost identical relationship, even though, in terms of both latitude and elevation, Calmar is closer

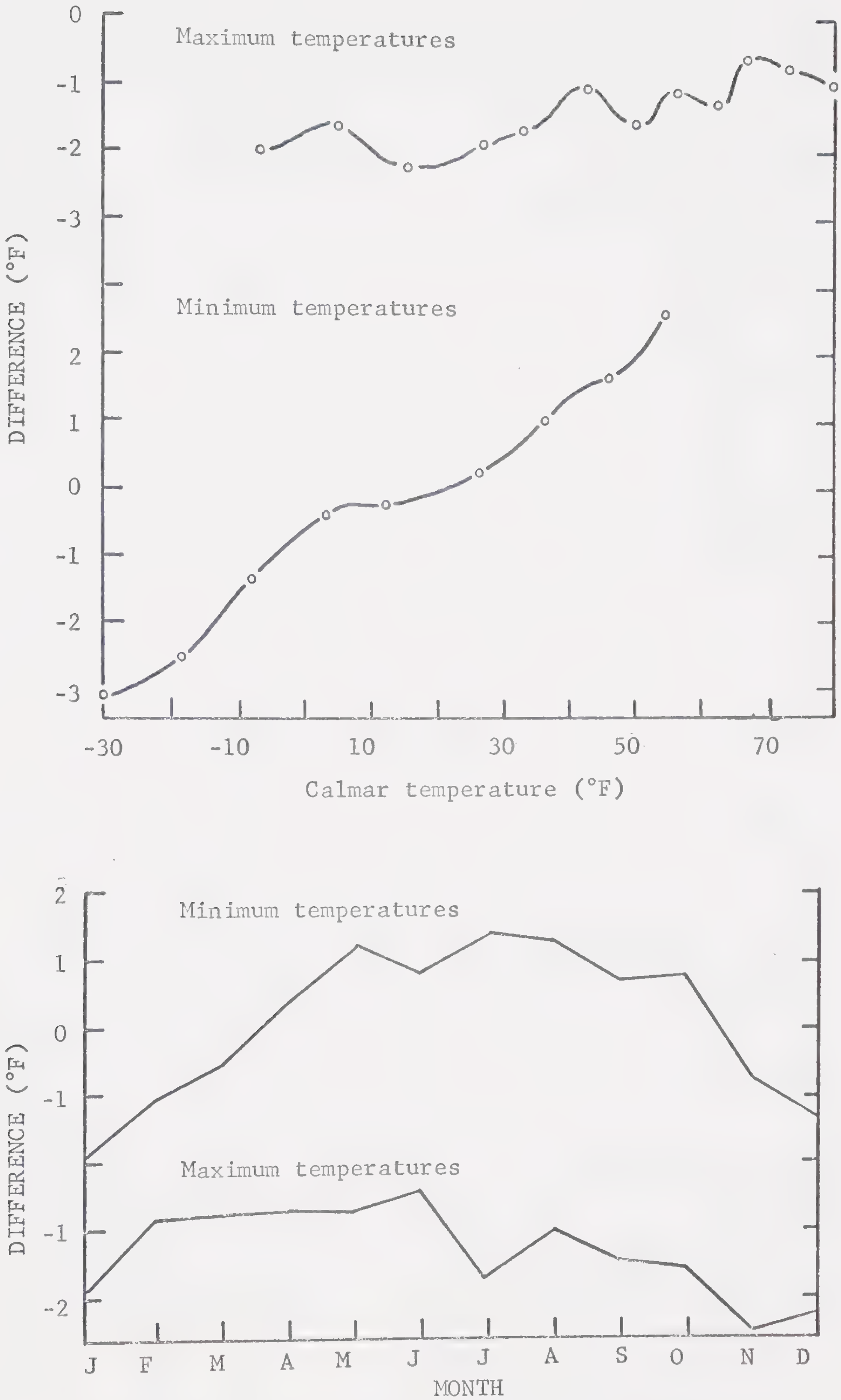
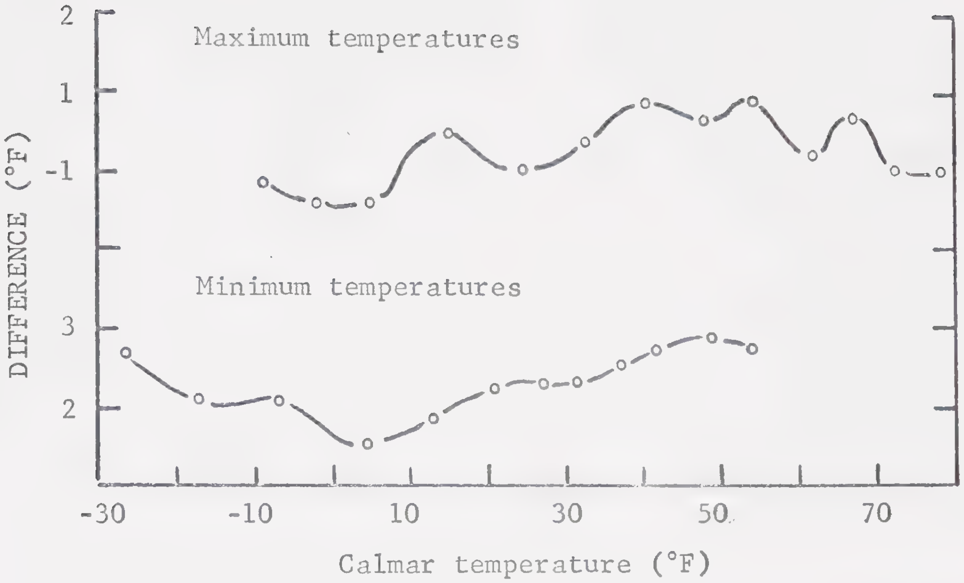


Fig. V-9. Mean Edmonton-Wetaskiwin temperature differences for the period 1931 to 1940. The lower graphs give differences on a monthly basis. The upper graphs give differences as a function of Calmar maximum temperatures (in the case of maximum temperature differences) and Calmar minimum temperatures (in the case of minimum temperature differences).



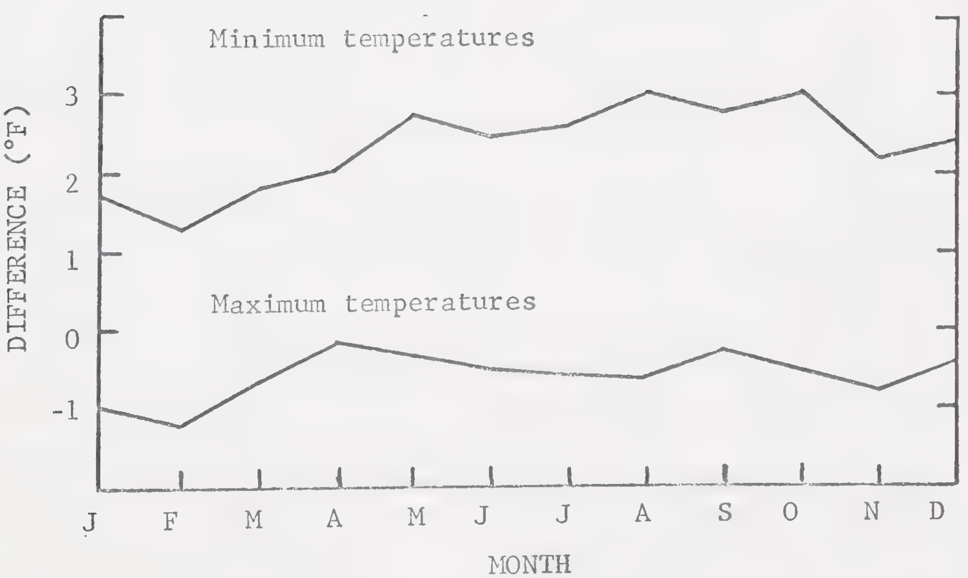


Fig. V-10. Mean Edmonton-Wetaskiwin temperature differences for the period 1956 to 1965. The upper graphs give differences as a function of Calmar maximum temperatures (in the case of maximum temperature differences) and Calmar minimum temperatures (in the case of minimum temperature differences).

than Wetaskiwin to Edmonton. Second, Fig. V-9 indicates that the rapid change in difference with temperature exhibited by the Edmonton-Wetaskiwin minimum values was present to only a slight degree for the maxima. While it would be unreasonable to expect both curves to be identical, it is difficult to explain such large discrepancies if only elevation and latitude effects were involved.

In the 1931-40 period, the seasonal variation in Edmonton-Wetaskiwin temperature differences for maximum values differed considerably from its counterpart for the minima. Here, the difference was smallest in the spring, with Edmonton becoming relatively cooler through the summer and fall. The largest difference was in November.

By the 1956-65 period, the Edmonton-Wetaskiwin differences for minimum values had become much less dependent on temperature, apparently because of the fact that the city had warmed most at lower temperatures. To a lesser extent, this was also true for maximum values, with the strongest warming having occurred in fall and early winter.

Comparing Fig. V-8 and Fig. V-10, it can be seen that the nature of Edmonton's apparent warming, as indicated by the change in the Edmonton-Wetaskiwin minimum temperature difference, showed little resemblance to the actual difference in the 1956-65 period. It is therefore apparent that a simple comparison between temperatures at the two sites for a specific period would reveal little about urban influences. The relatively large difference in location makes this an extreme case. Nonetheless, it seems reasonable to be skeptical of the numerous studies which purport to show the effects of a city on temperature through a single-period comparison.

Distribution of Differences

Another insight into the nature of Edmonton's temperature change over

the years can be gained from Figs. V-11, V-12, V-13, and V-14. For given time periods, these bar graphs give the percentage of days in which the Edmonton-Wetaskiwin temperature differences were of the magnitude given on the horizontal axes.

It is worthwhile to consider theoretically what effect the development of an urban heat island would have on this type of distribution. To do this, consider the ideal case where there are initially two rural stations whose temperatures, in the mean, are identical. Fig. V-15 gives a binomial distribution of temperature differences that might develop from the effectively random influences of differing weather situations. If the distribution is considered as being Station 1 minus Station 2, it is now possible to consider what change will occur if rural Station 1 becomes a major urban area with a considerable heat island effect. Two simple models of this heat island are possible. Consider first one in which only a certain percentage of the days shows an urban influence. This would be in accord with the discussion of Fuggle and Oke (1968), where a critical wind velocity was given above which the heat island ceased to exist (see Fig. II-1). To be more specific, consider a model in which 50% of the days show no temperature change as a result of urban development, 30% show a 3°F increase, 15% show 6°F, and 5% show 9°F. Alternately, consider a model in which all days show some effect. Let the percentage of days with a given increase be as follows: 10%, 1°F; 20%, 2°F; 40%, 3°F; 20%, 4°F; 10%, 5°F.

Assuming all days are equally susceptible to warming, the results of superposing the first and second model onto the original distribution are shown in Fig. V-15. It can be seen that the model using a "cutoff" produces a distinct rightward skew in the distribution. City-country differences computed by Landsberg (1956) appear to show this effect, as

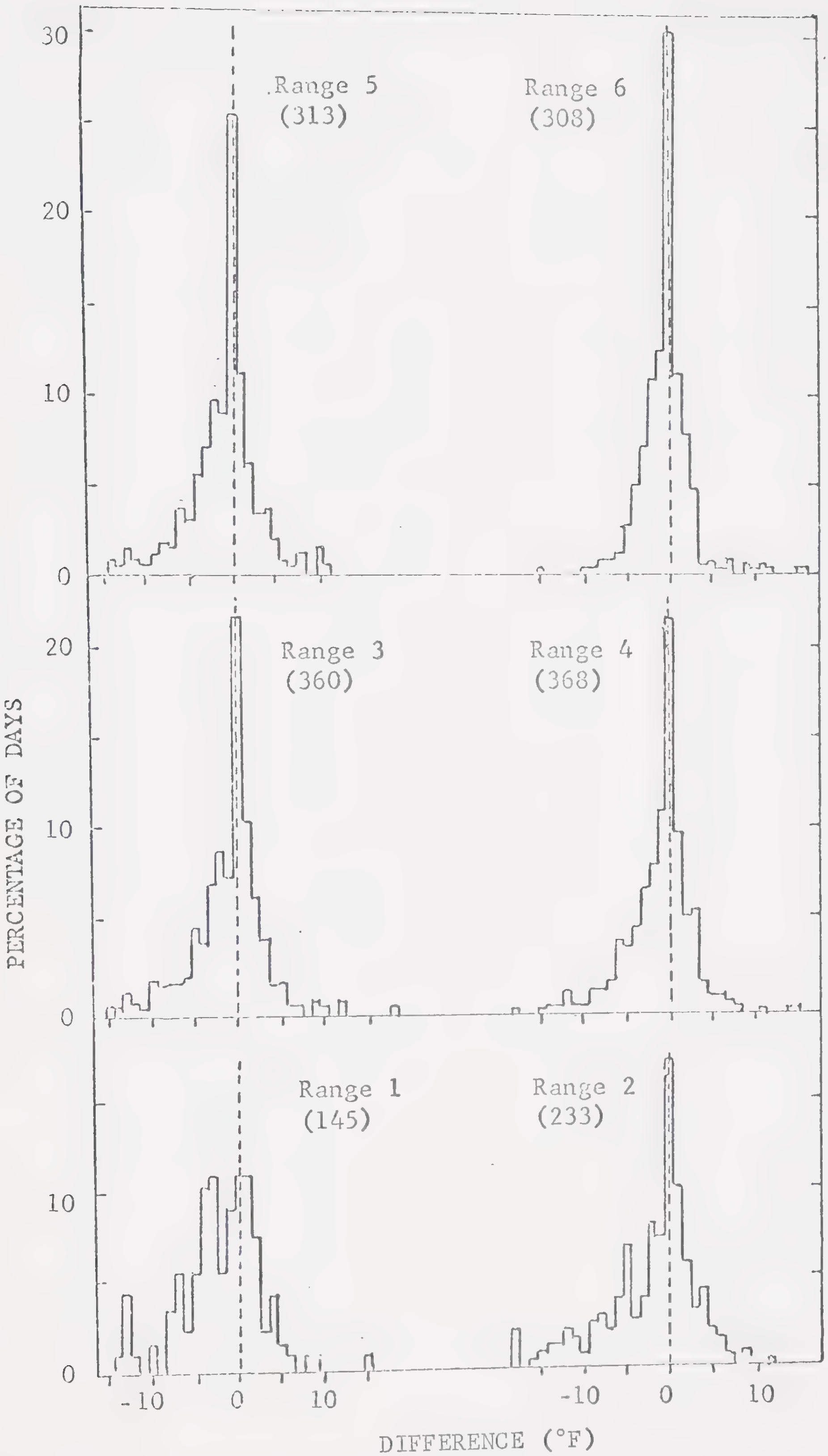


Fig. V-11. Percentage frequency of Edmonton-Wetaskiwin maximum temperature differences for the period 1931 to 1935. (Values in brackets indicate the number of cases.)

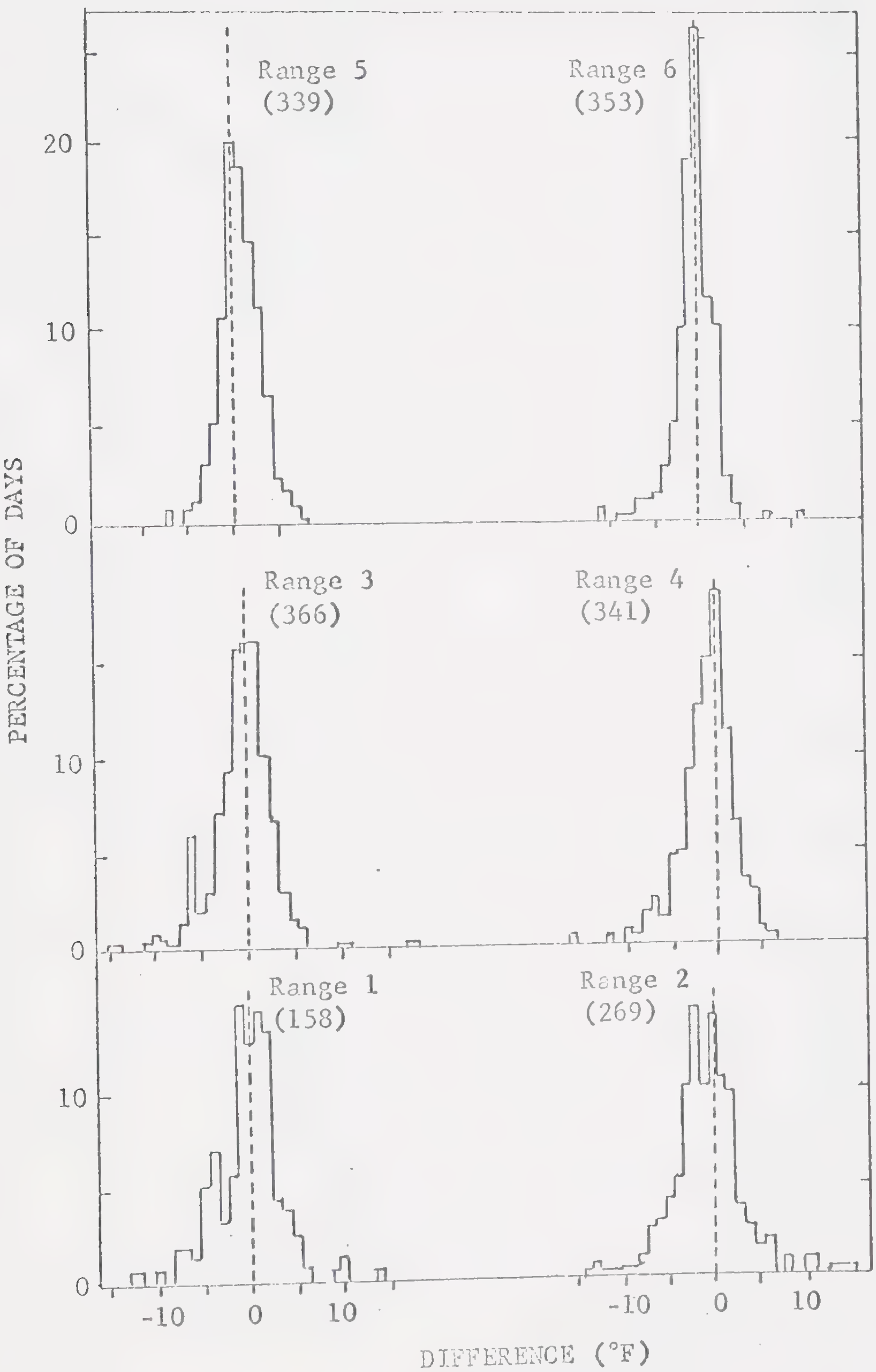


Fig. V-12. Percentage frequency of Edmonton-Wetaskiwin maximum temperature differences for the period 1951 to 1955. (Values in brackets indicate number of cases.)

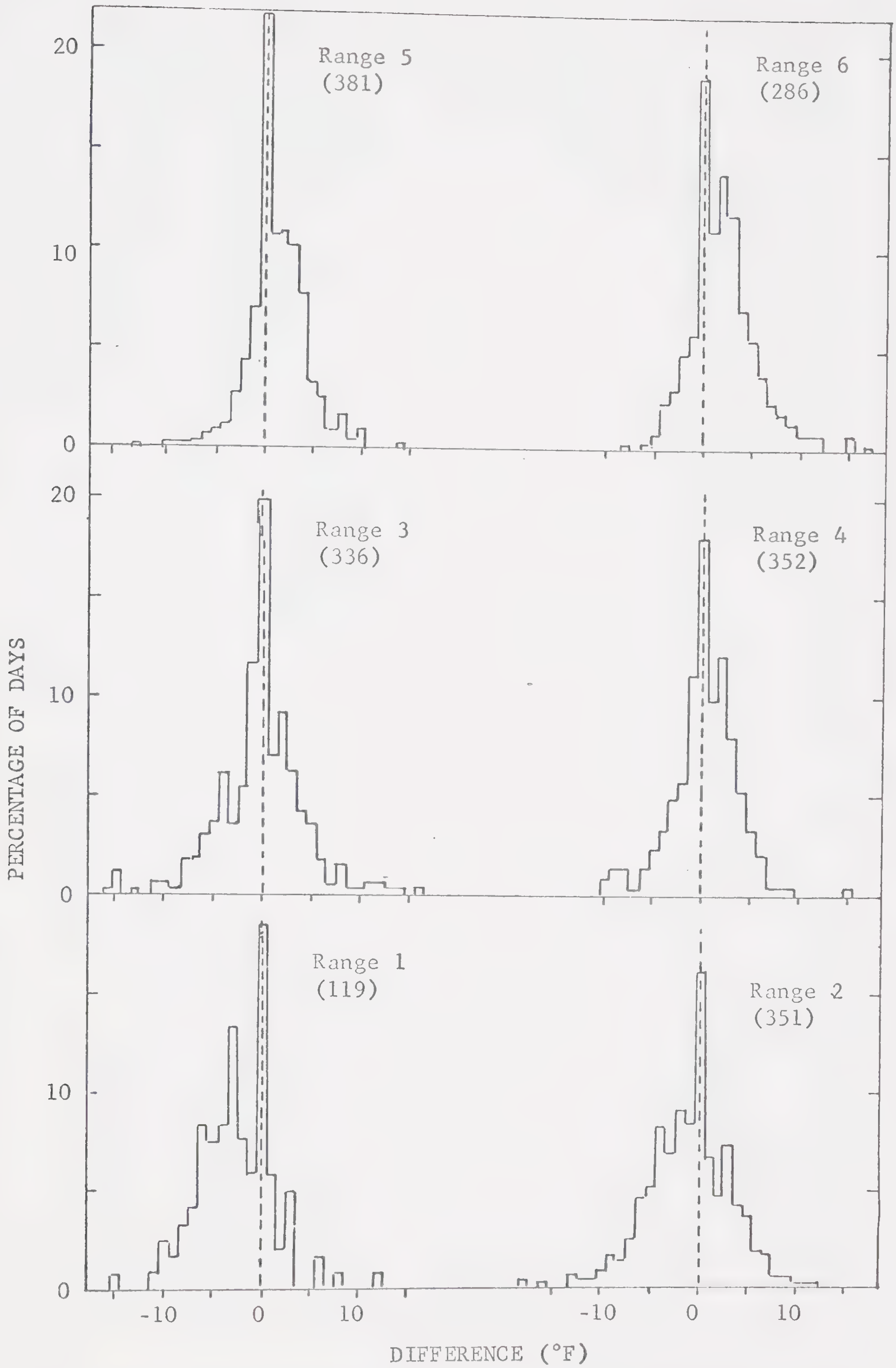


Fig. V-13. Percentage frequency of Edmonton-Wetaskiwin minimum temperature differences for the period 1931 to 1935. (Values in brackets indicate number of cases.)

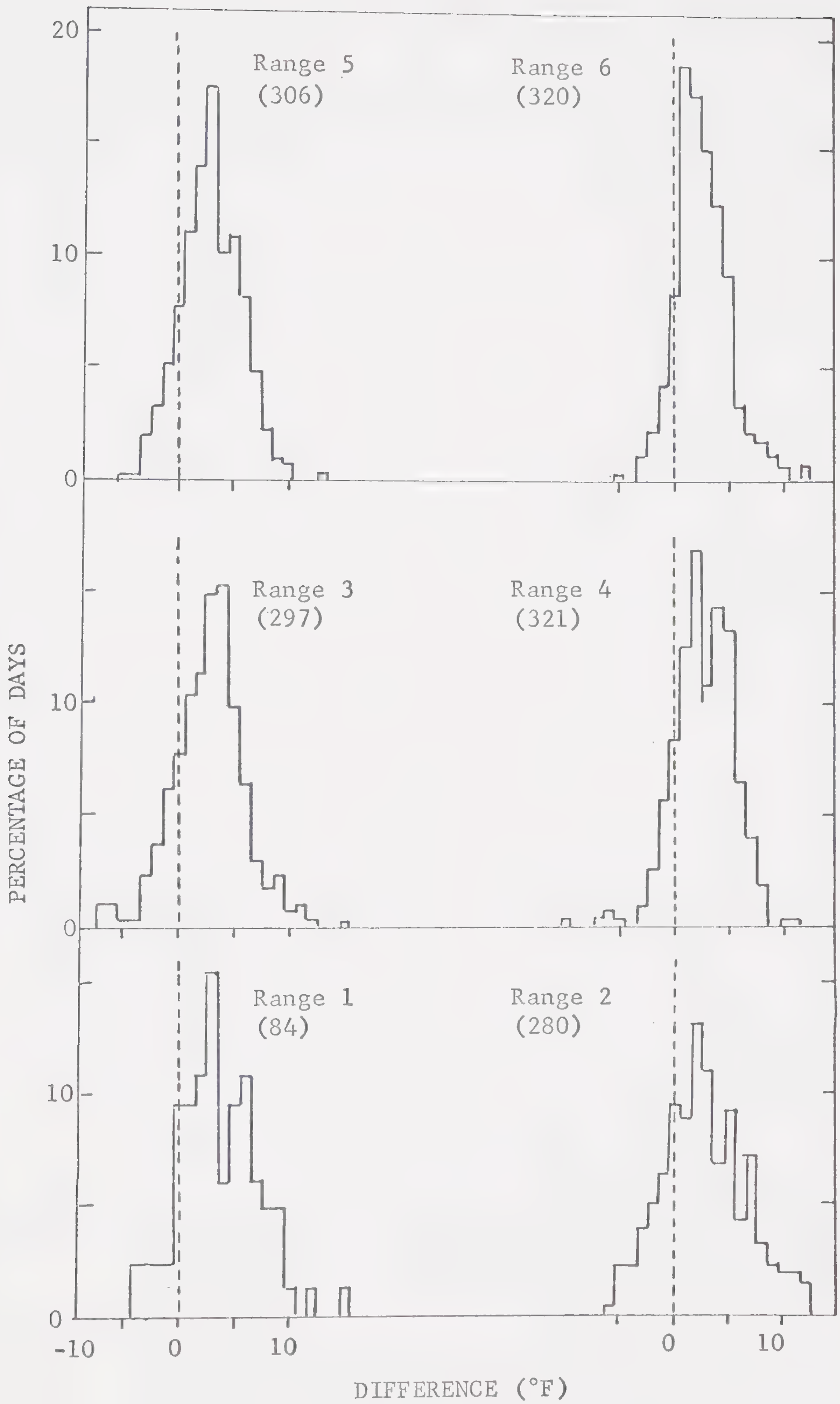


Fig. V-14. Percentage frequency of Edmonton-Wetaskiwin minimum temperature differences for the period 1956 to 1960. (Values in brackets indicate number of cases.)

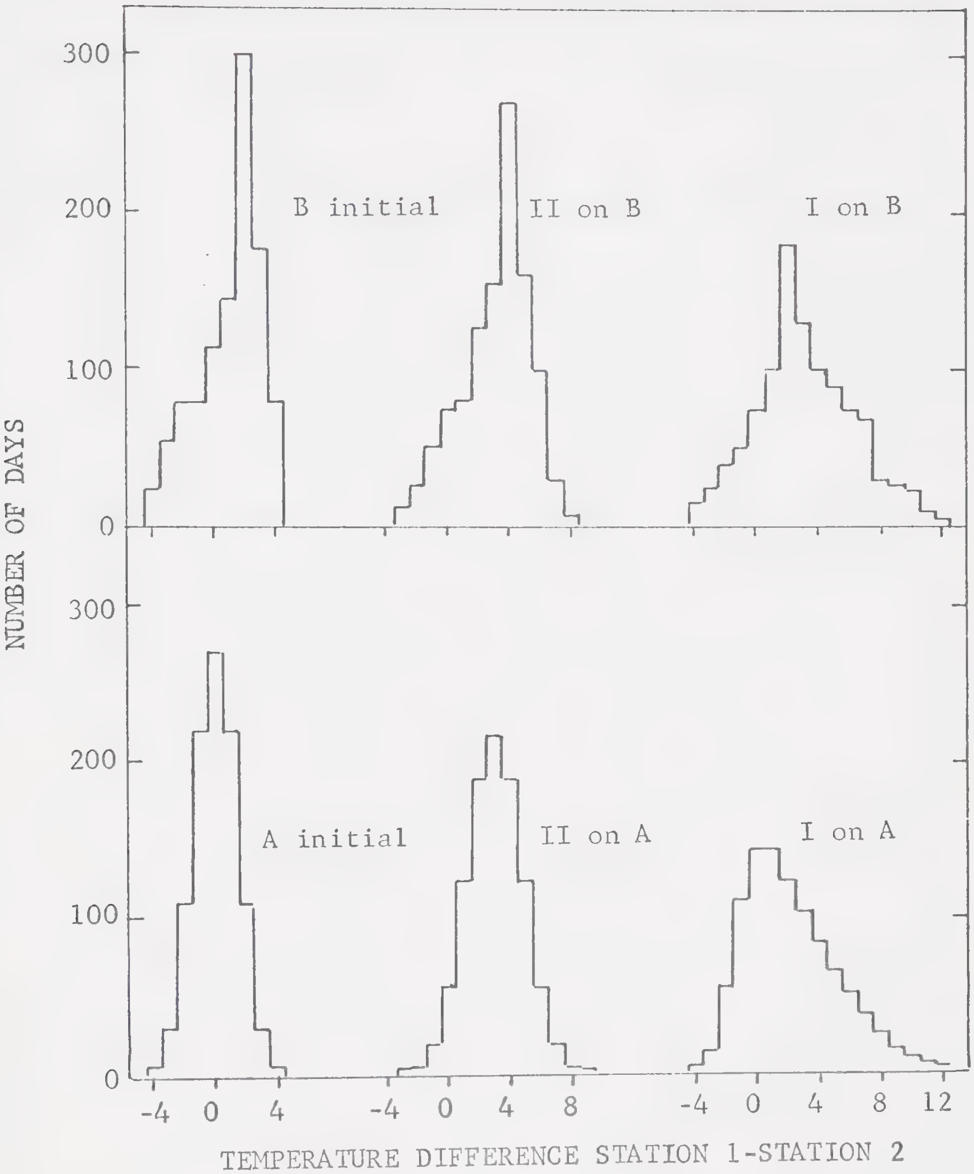


Fig. V-15. The effects of two types of warming (I and II) at one station on distributions of temperature differences between it and another station. The initial distributions are random (binomial) (A) and left-skewed (B).

Type of warming (on station 1):

% of days	temp. change
10	1
20	2
40	3
20	4
10	5

(Type II)

% of days	temp. change
50	0
30	3
15	6
5	9

(Type I)

can be seen from Fig. V-16. In the case of the second model, in which all days are affected, there is no skewing, or in other words, symmetry is maintained. In both cases the standard deviation is increased, with the maximum being less sharp. This is especially true for the "cutoff" model.

Fig. V-15 also includes the effects of superposing the first and second models given above on a distribution initially skewed to the left. In these two cases the slope of both sides of the distribution becomes more gradual. This is especially true for the right side in the case of the model in which only some of the days are affected.

Returning now to the bar graphs for maximum temperatures (Fig. V-11 and Fig. V-12), it is apparent that, for the early 1931-35 period, the distributions of Edmonton-Wetaskiwin differences were not normal, but showed a pronounced skewing to the left, especially at low temperatures. Except for Range 1 there was, however, a distinct maximum at zero difference. By the later 1951-55 period, there was a considerable change in the distributions of these maximum values, at least for Range 1 to Range 4, where Edmonton's warming was substantial. The distinct maximum at zero difference diminished somewhat, as would be expected for the model. These distributions differ from the skewed model in that, after warming, there was a much sharper drop from the maxima toward negative values. Going toward positive values, the slope remained much the same.

In order to explain the above differences, consider specifically Range 2 for maximum temperatures. In the earlier period, Edmonton was warmer than Wetaskiwin on 31 per cent of the days. By the later period, this percentage had increased only slightly to thirty-four. On the other

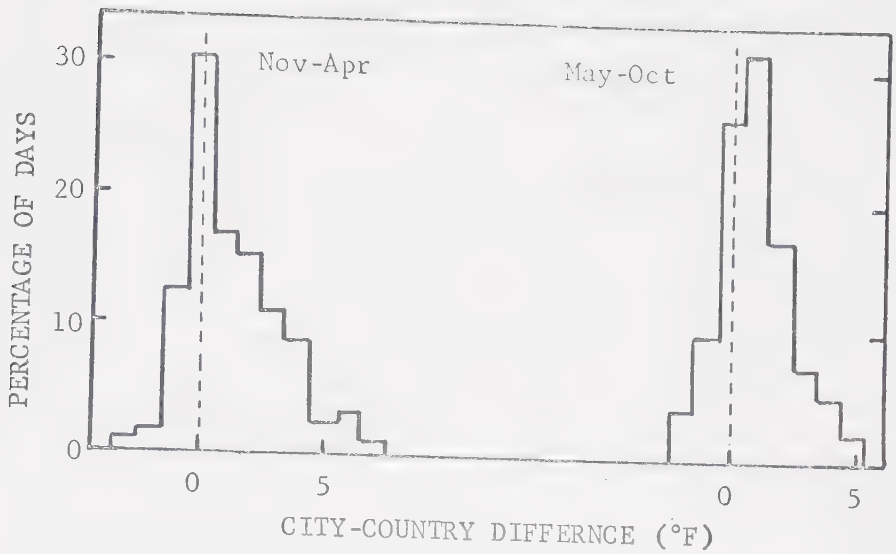


Fig. V-16. Percentage frequency of minimum temperature differences between urban and rural sites for Lincoln, Neb. Source: Landsberg (1956).

hand, between the same two periods, the number of days with Edmonton more than 4°F colder than Wetaskiwin dropped sharply, from 30 per cent to 14 per cent. The amount of warming was sufficient to increase the number of days in the category in which Edmonton was slightly cooler than Wetaskiwin. However, this warming did not affect, to any appreciable extent, the part of the distribution in which Edmonton was originally warmer. It follows that the set of days which was most susceptible to warming contained those days in which Edmonton was coldest (in the 1931-40 period) with respect to Wetaskiwin.

The explanation of the above effect probably depends, at least in part, on the difference in elevation between the two stations. Wetaskiwin, being higher, would tend to be relatively warmer under stable conditions. This stability would normally mean less vertical mixing and lighter winds, hence these days should have been more susceptible to urban influences.

From Fig. V-13 and Fig. V-14 it can be seen that the distributions of temperature differences for minimum temperatures differed somewhat from those for maximum values. In the 1931-35 period, distributions of both maximum and minimum temperatures were left-skewed at low temperatures (Range 1 and Range 2). However, in warmer weather (Range 5 and Range 6), the distributions of minimum temperature differences were right-skewed, while those for maximum temperature differences remained skewed to the left. This change from a left-skew in colder weather to a right-skew in warm weather may have been related to latitude effects, which would tend to make Wetaskiwin warmest, relative to Edmonton, on colder days. The increased sharpness of the drop from the maximum toward negative values in the period 1956-60 was indicative of the fact that the set of days which underwent the greatest amount of warming consisted of those days in which Edmonton, in the 1931-40 period, was coldest relative to Wetaskiwin. This pattern of warming was similar to that of the maximum temperatures.

Time Series for Large Edmonton-Wetaskiwin Differences

The nature of Edmonton's warming, as discussed in the preceding section, can be seen in a simpler way by consideration of Fig. V-17 and Fig. V-18. To compute these time series, the 10-percentiles of those days in which Edmonton was warmest in relation to Wetaskiwin have been taken on a temperature-range basis. The values plotted are the five-year running means of the mean difference between the two stations for these selected sets.

For Range 1 of the minimum temperatures, it is apparent that the mean difference for the 10-percentile of days with the largest difference generally increased for the post 1940 period, although at a much dimin-

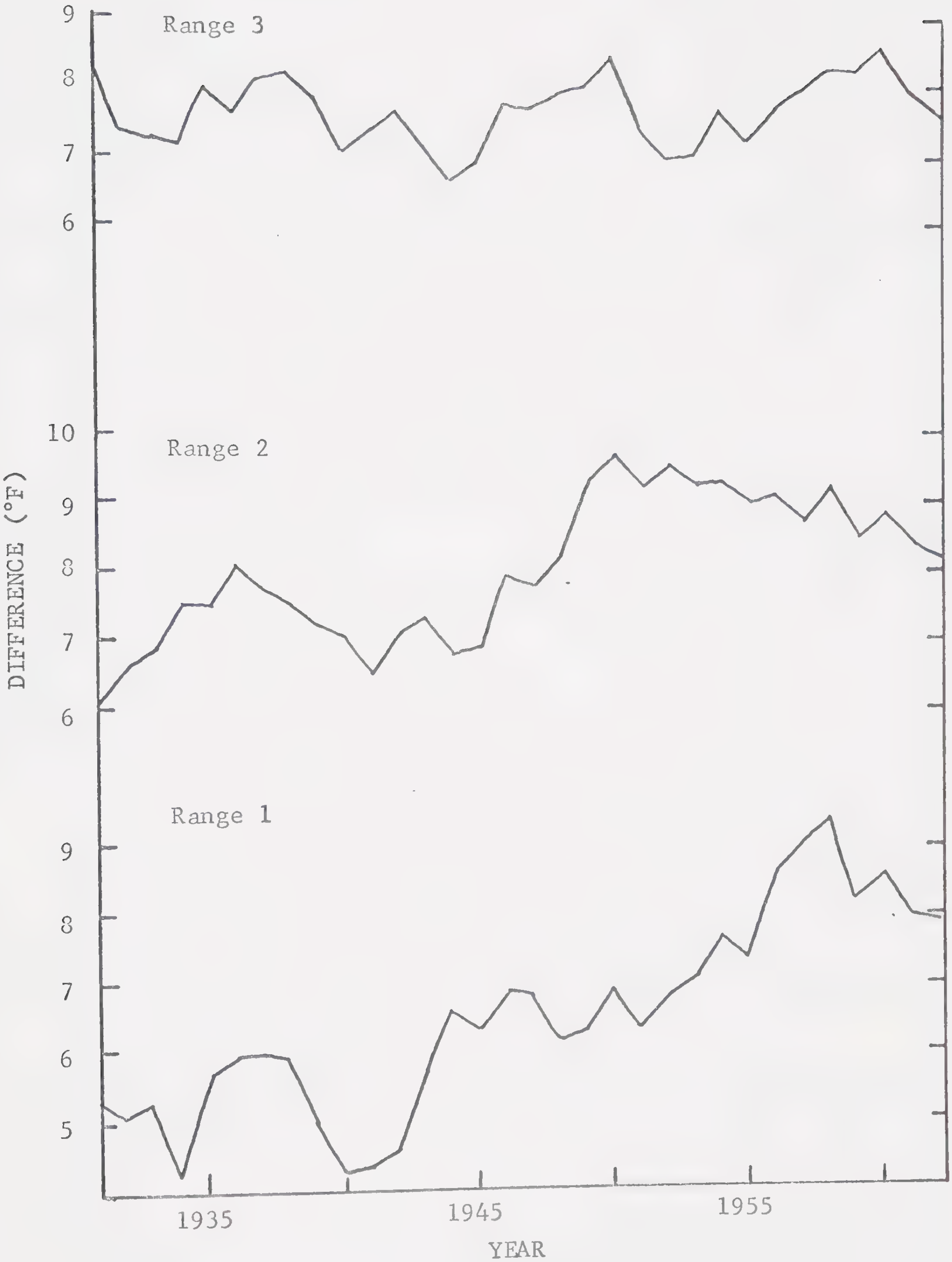


Fig V-17a. Five-year running means of the Edmonton-Wetaskiwin temperature difference for the 10-percentile of those days upon which the difference was largest. Values are for minimum temperatures by range.

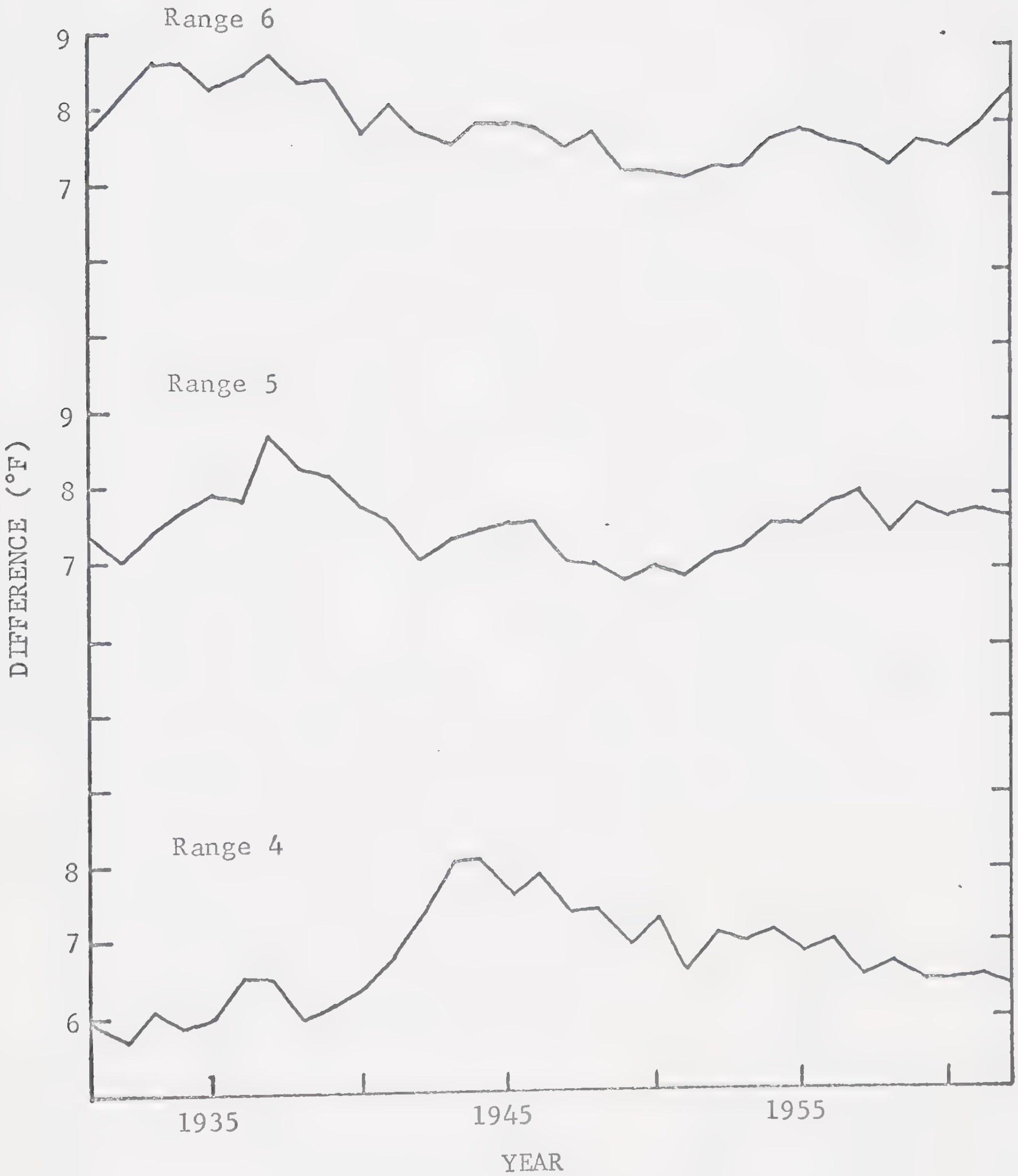


Fig. V-17b. Five-year running means of the Edmonton-Wetaskiwin temperature difference for the 10-percentile of those days upon which the difference was the largest. Values are for minimum temperatures by range.

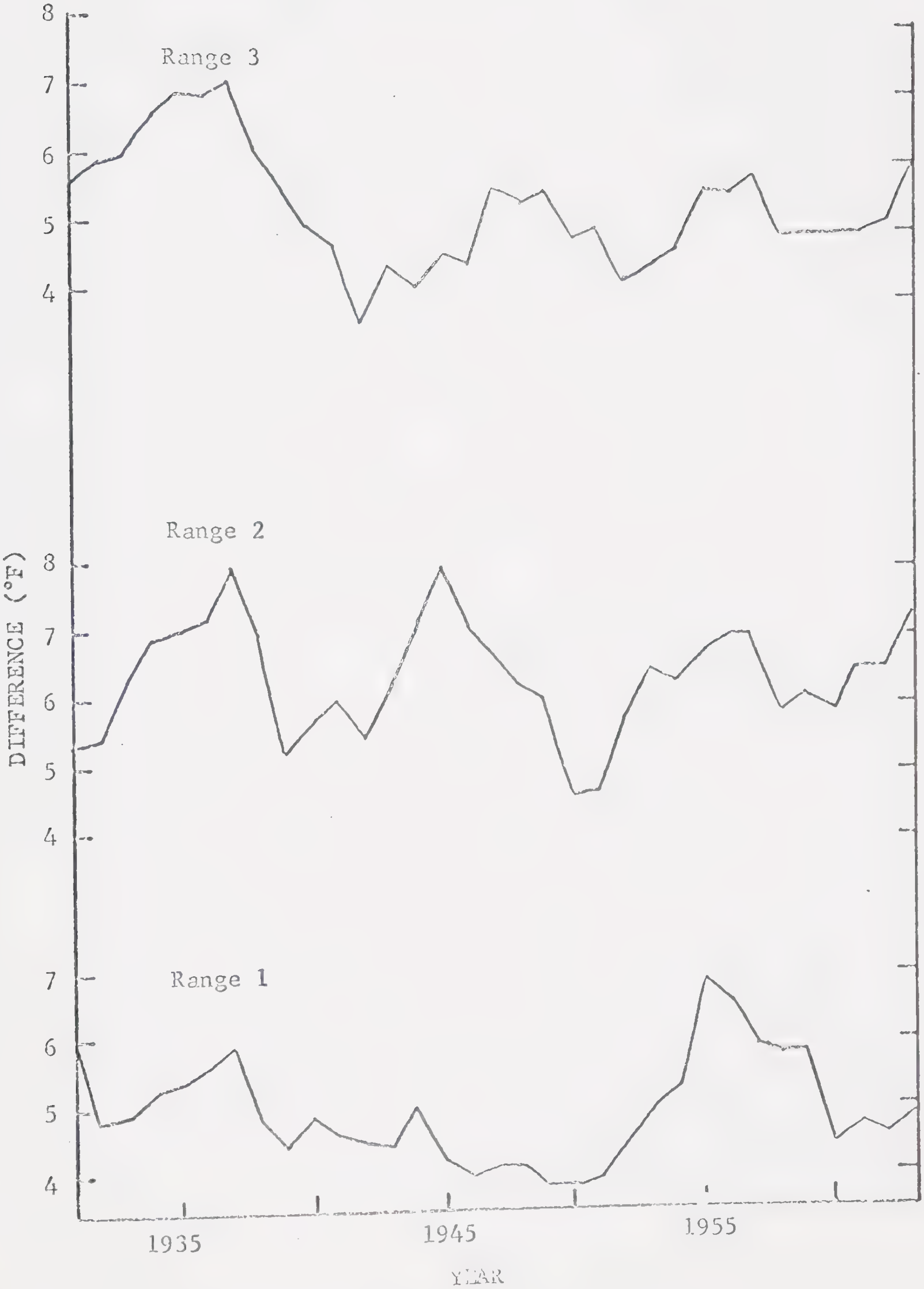


Fig. V-18a. Five-year running means of Edmonton-Wetaskiwn temperature differences for the 10-percentile of those days in which the differences were largest. Values are for maximum temperatures by range.

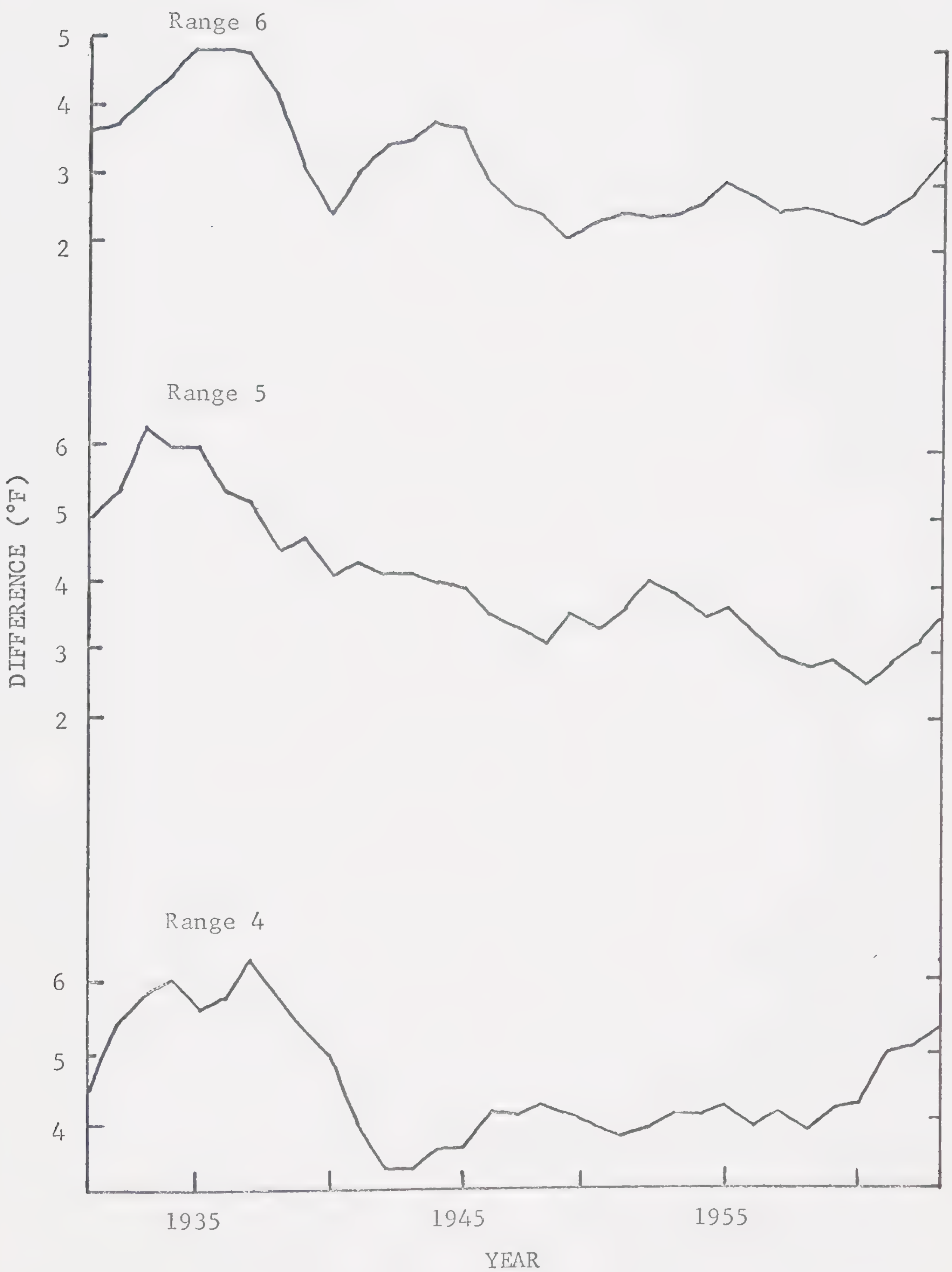


Fig. V-18b. Five-year running means of Edmonton-Wetaskiwin temperature differences for the 10-percentile of those days in which the differences were the largest. Values are for maximum temperatures by range.

ished rate from the set including all days within the range (compare Fig. V-6). For the remainder of the minimum temperature ranges in Fig. V-17, there is little evidence of the apparent increase in Edmonton temperature with time manifested by the mean difference derived from all days in the range. Figs. V-2 and V-18 show similar results for maximum temperatures. In accord with the discussion of the bar graphs, these results point to the fact that, excluding very low minimum temperatures, there was, generally speaking, a set of days which was little affected by the city's general warming. This set consisted of days in which Edmonton initially had the greatest positive difference relative to Wetaskiwin. As discussed previously, stability considerations may play a major part in the explanation of this phenomenon.

Effects of Cloud and Precipitation

It was desired to estimate the influence of cloud cover on the apparent warming of Edmonton. Because cloud-cover data were not available in suitable form, it was found necessary to use precipitation as an index. Observations were divided into those days having precipitation (more than a trace) and those days without. It was then assumed that, in the mean, cloud cover would be greatest on those days with precipitation. Obviously, this method gives a rather rough estimate of cloud. This is especially true in the case of the Edmonton area, where long periods of cloud cover may occur with little precipitation. In late spring and summer, the fact that much precipitation results from showers associated with brief afternoon or evening cloudiness could be another weakness.

In spite of these difficulties, it is of interest to consider the results of this approach, as indicated in Table V-1, which gives values of the Edmonton-Wetaskiwin temperature difference divided into precipitation and no-precipitation categories. Ranges are given in groups of

TABLE V-1 - EDMONTON-WETASKIWIN TEMPERATURE DIFFERENCES ON DAYS WITH (P.) AND WITHOUT (No.P.) MEASURABLE PRECIPITATION AT EDMONTON

		Range 1&2		Range 3&4		Range 5&6	
		No. P.	P.	No. P.	P.	No. P.	P.
Max. temp.:	1931-40	-2.1	-2.4	-1.2	-2.3	-0.5	-1.6
	1956-65	-1.2	-0.2	-0.4	0.4	-0.7	-0.8
	change	0.9	2.2	0.8	1.9	-0.2	0.8
Min. Temp.:	1931-40	-1.5	-1.4	-0.4	-0.3	1.8	1.4
	1956-65	2.4	1.3	2.7	1.3	3.1	2.1
	change	3.9	2.7	3.1	1.6	1.3	0.7

two because of the relatively small number of days with precipitation. In the case of maximum values, Edmonton was, relatively speaking, coolest on precipitation days in the 1931-40 period. By the 1956-65 period there was a distinct reversal, with the city being relatively cooler on "dry" days. Apparently then, the warming of Edmonton at maximum temperature time was much greater on precipitation days. For minimum temperatures the situation was quite different. Here, the days without precipitation underwent by far the greatest warming in the city.

In interpreting these results it must first be asked whether the changes were actually a result of differing amounts of cloud cover, or some other effect. For example, the greater amount of warming on "wet" days in the city for maximum temperatures could have been a result of reduced loss of heat to evaporation because of more efficient drainage. This type of question cannot be answered definitely; hence the problem is reduced to a search for the most plausible explanation. In view of the fact that variations in cloud cover have a well established influence on city temperature, it seems logical to attempt to explain the

observed data in terms of this factor.

The fact that for maximum temperatures in the 1931-40 period, Edmonton was warmest relative to Wetaskiwin on "dry" days could have resulted from the fact that relatively cloud-free air masses are more subject to heating from below, and hence tend to be more unstable. Wetaskiwin's higher elevation would have consequently made it relatively cooler. This effect is probably least in winter when insolation is weak. This is borne out by the data. Another factor could involve the frequent association of precipitation with frontal activity, which would tend, in the mean, to increase the north-south temperature gradient.

During the day, the increased surface heating associated with smaller cloud amounts should tend to cause increased instability. The net result would be to increase mixing over the city and consequently enhance the dissipation of excess urban heat, making city temperatures more homogeneous with those of the surrounding area. Assuming that days without precipitation have less cloud than those with precipitation, it would be expected, therefore, that the former days would show less increase in temperature as a result of urban expansion. This is in accord with the maximum temperature data.

For the minimum temperatures the situation is somewhat different. Nights with less cloud tend to favor low-level stability as a result of more intense radiational cooling. Consequently, assuming that dry days have less nighttime cloud, it seems reasonable to expect that urban influences, as reflected in these temperatures, should be greatest on those days showing no precipitation. Again, the tabulated changes in the Edmonton-Wetaskiwin differences for minimum temperatures bear this out.

Sufficient data are lacking to either confirm or deny the above. However, under the circumstances, it seems to be the most reasonable explanation of the results.

CHAPTER VI

THE INFLUENCE OF VARIOUS METEOROLOGICAL FACTORS

Problems Involved

In attempting to gauge the effects of urban expansion on Edmonton temperature by use of time series of Edmonton-Wetaskiwin temperature differences, it is pertinent to ask what other factors could have been influential. In view of the fact that the city-country temperature difference depends to a great extent on the prevailing weather, it is not unreasonable to expect that year-to-year variations in such things as temperature and wind could have caused fluctuations in these series of differences. Additionally, these weather variations could have acted to influence the Edmonton-Wetaskiwin difference in ways unrelated to the urban regime. The previously-postulated effects of weather, arising from the difference in location of the two stations, are perhaps the most likely source of difficulty in this regard.

In theory, the obvious approach to this problem would be the determination and isolation of influential factors not directly related to urban expansion. In practice, for a number of reasons, this approach is difficult in the extreme. One major problem involves the lack of adequate theoretical understanding of the mechanisms controlling urban climate. Additionally, the various meteorological factors are interrelated in complex ways which vary from season to season. On a more practical level, available data may not have been sufficiently detailed to allow effective assessment of their roles. No values were available on an hourly basis.

Only precipitation and temperature were available on a daily basis.

It is not intended to suggest that the above problems are insurmountable. An attempt to determine the influences of fluctuations in meteorological factors will be made subsequently. It is possible that, with more detailed data and relatively sophisticated statistical techniques, considerably more progress could be made.

Correlation and Comparison

In a first attempt to determine what influence the above-discussed variations in weather could have had on the time series of Edmonton-Wetaskiwin temperature differences, correlation coefficients were computed. Values were computed between differences on one hand, and temperature, sunshine, wind speed, and the number of days with precipitation on the other. Computations were done on yearly, monthly, and temperature range bases. Generally speaking, significant correlations did not appear. The few values which could conceivably be construed as significant will be discussed subsequently.

In addition to the difficulties discussed in the first section of this chapter, there are two probable causes for the failure of this correlation technique. First, there were strong trends in the data (e.g., 1948-58 for the yearly maximum differences, as in Fig. V-1). The second possible reason, which is not entirely without merit, is that the fluctuation of meteorological factors may have had no significant effect on annual mean differences.

In addition to the use of correlation coefficients, a second technique was employed in an attempt to relate variations in station differences to variations in other factors. Although devoid of the impressive theoretical trappings which tempt the use of more esoteric methods, it

nonetheless commends itself, if for no other reason than simplicity. This technique involves the simple visual comparison of the time series of such factors as sunshine and wind with the series of Edmonton-Wetaskiwin temperature differences.

The Influence of Meteorological Factors on Maximum Temperatures

Referring back to Fig. V-1, which gives yearly values of the Edmonton-Wetaskiwin maximum temperature differences from 1929 to 1967, it can be seen that the curve contains a number of features of considerable interest. The first is the upward trend in differences occurring from the mid-forties to the mid-fifties. This period of increase coincided with a period of rapid expansion of the city (see Fig. III-3), and it is not unreasonable to suspect that the two factors were related. The two major minima in this difference curve, occurring around 1940 and 1960, complicate the picture, however. These minima, for the most part, remain when the data are subdivided into ranges or months, as can be seen from Fig. V-2 and Fig. V-3.

The question immediately arises as to what extent these minima, and indeed the general shape of the maximum temperature-difference curves, can be attributed to fluctuations in meteorological factors. As stated previously, attempts to relate these factors to the differences failed in general. One possible exception was the -0.54 correlation coefficient (significant at the 99.5 per cent level from a t-Test) found between yearly mean values of Edmonton-Wetaskiwin maximum temperature differences and Calmar maximum temperatures. (The reason for the use of the somewhat defective Calmar data for this type of comparison is discussed in the final portion of this chapter.) This inverse relationship between maximum temperature and difference can be seen clearly in Fig. V-1. The

two minima in yearly maximum differences occurring around 1940 and 1960 corresponded to the periods when maximum temperatures were the highest. Conversely, the two periods when these differences appear to have been greatest corresponded to cold periods. Although this hardly constitutes proof of a cause-and-effect relationship, there is certainly an indication of some degree of dependence.

Postulating this relationship between temperature and difference immediately presents one difficulty. When introducing the classification of data into temperature ranges, it was pointed out that, for Range 2 to Range 5 at least, yearly fluctuations in mean range temperatures were small. If the two major minima in the difference curves were a reflection of variations in maximum temperatures, the question arises as to why these minima appear in Range 2 to Range 5 data (Fig. V-2) which have this constancy in mean temperature.

One possible explanation is as follows. Even though the year-to-year variations in mean temperature within these ranges were small, it is conceivable that yearly fluctuations could have affected the computed differences in a more indirect manner. For example a given range could have had exactly the same mean temperature on two consecutive years, even though the first year was abnormally warm, the second abnormally cool. The given range would have differed between the two years, however. In the first case, the range would have tended to consist of days which were abnormally warm. In the cold year, temperatures would have tended to be below normal. It seems reasonable to expect these differences to be of some significance. For example, taking an extreme case, a very cold day in April, with a maximum temperature of 30°F, would be considerably different than an unusually mild day in January with the same

temperature.

In an attempt to determine the significance of this effect, the mean departure of maximum temperatures from normal was computed by year for each temperature range. Five-year running means of these values are given in Fig. VI-1 and Fig. VI-2. Calmar temperatures were used in the calculations, for reasons which will shortly be discussed. This use of Calmar introduced a degree of error into the data, as a result of the fact that, relative to other observing stations in this area, its maximum temperatures increased in the late 1940s. The relative magnitudes of these changes in Calmar temperatures can be assessed from Fig. VI-1 and Fig. VI-2, which include Wetaskiwin-Calmar temperature differences for each range given. It is apparent that, for Range 3 to Range 6 at least, the relative change in Calmar values was small in comparison with the yearly changes in departures. In other words, for these ranges, discrepancies in the Calmar data did not appreciably distort the time series of Calmar departures. In Range 2, the warming of Calmar relative to the other stations in the area was substantial around 1949. The broken line in Fig. VI-1 represents the estimated adjustment required to correct the Calmar departures for this change.

Correlation coefficients were calculated between Edmonton-Wetaskiwin maximum temperature differences and the departures from normal at Calmar. The values are given on a range-by-range basis in Table VI-1. These figures suggest that, for Range 2 to Range 6, differences were inversely related to the departure of temperature from normal. In other words, abnormally cool weather was accompanied by the largest Edmonton-Wetaskiwin maximum temperature differences, and vice versa. This is in accord with the previously-mentioned fact that, on a yearly basis, maximum

TABLE VI-1 - CORRELATION COEFFICIENTS (r) BETWEEN EDMONTON-WETASKIWIN MAXIMUM TEMPERATURE DIFFERENCE AND DEPARTURE OF CALMAR MAXIMUM TEMPERATURE FROM NORMAL

Range	1	2	3	4	5	6
r[a]	-.06	-.28	-.30	-.53	-.51	-.25

[a]The 95% significance level (t-Test) is about -.30

temperatures and differences were negatively correlated.

This relation between differences and departures probably explains, to some extent at least, why subdividing the differences into ranges failed to eliminate the 1940 and 1960 minima which appeared in the yearly mean values. The fact that the departure of temperature from normal could influence the value of the differences meant that classification of these differences into groups with little yearly temperature fluctuation did not eliminate the effects of year-to-year temperature changes.

It is worthwhile to consider the relationship between Calmar departures from normal and Edmonton-Wetaskiwin maximum temperature differences on a range-by-range basis, as shown in Fig. VI-1 and Fig. VI-2. The inverse relationship between these two factors, as indicated by the negative correlation coefficients, can be seen clearly. Of particular interest is the period of increasing differences extending from the 1940s to the 1950s. For Range 2 to Range 6, this increase was approximately coincident with a decline in departures. The decline in differences occurring in the late 1950s generally corresponded to an increase in departures. The exception was Range 4, where both departures and differences remained approximately constant after 1950. Range 1 has been omitted from this discussion. There was little apparent relationship

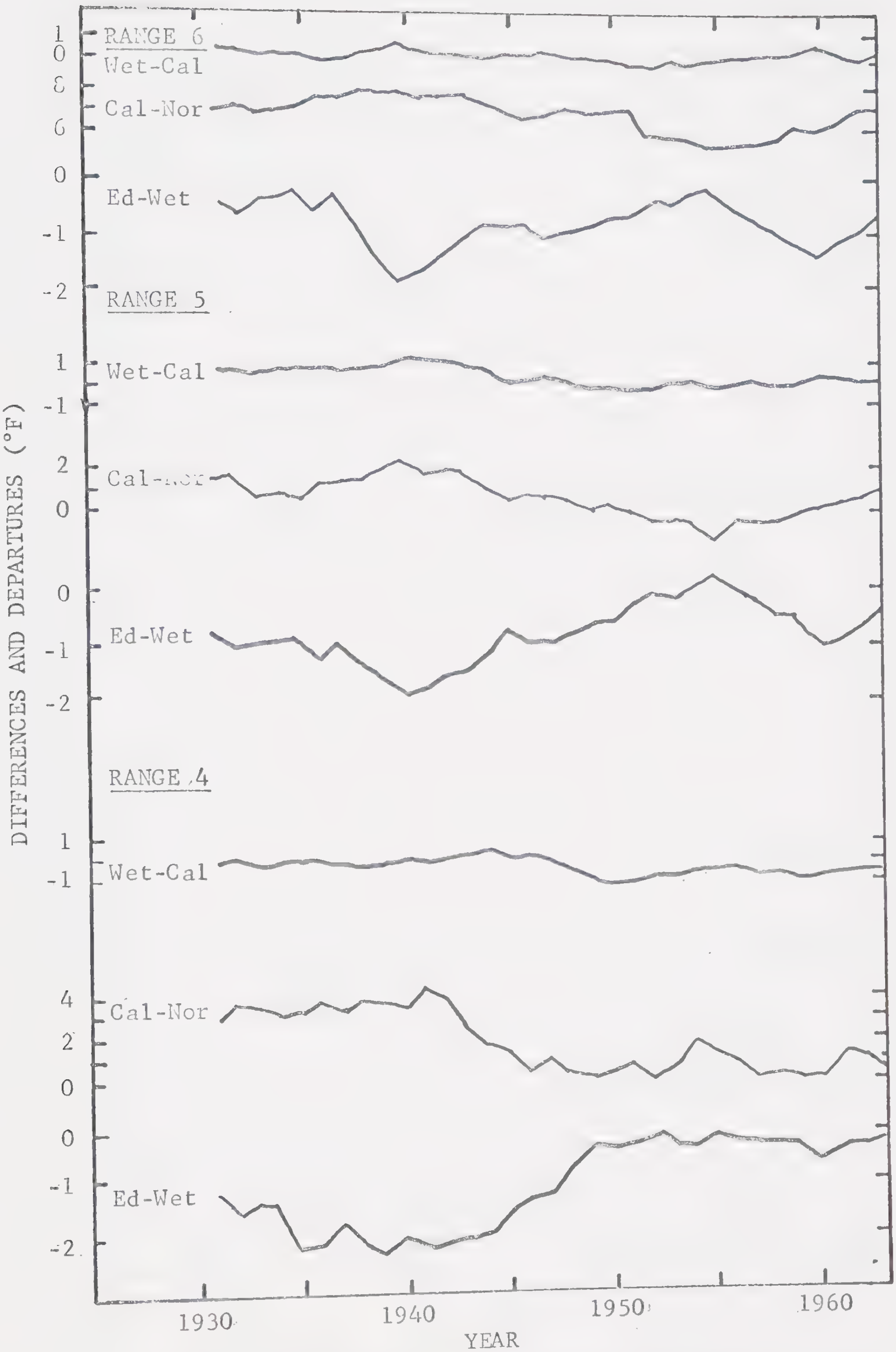


Fig. VI-1. Edmonton-Wetaskiwin (Ed-Wet) and Wetaskiwin-Calmar (Wet-Cal) maximum temperature differences for Ranges 2 and 3. Included are departures of Calmar maximum temperature from normal (Cal-Nor). All data are five-year running means.

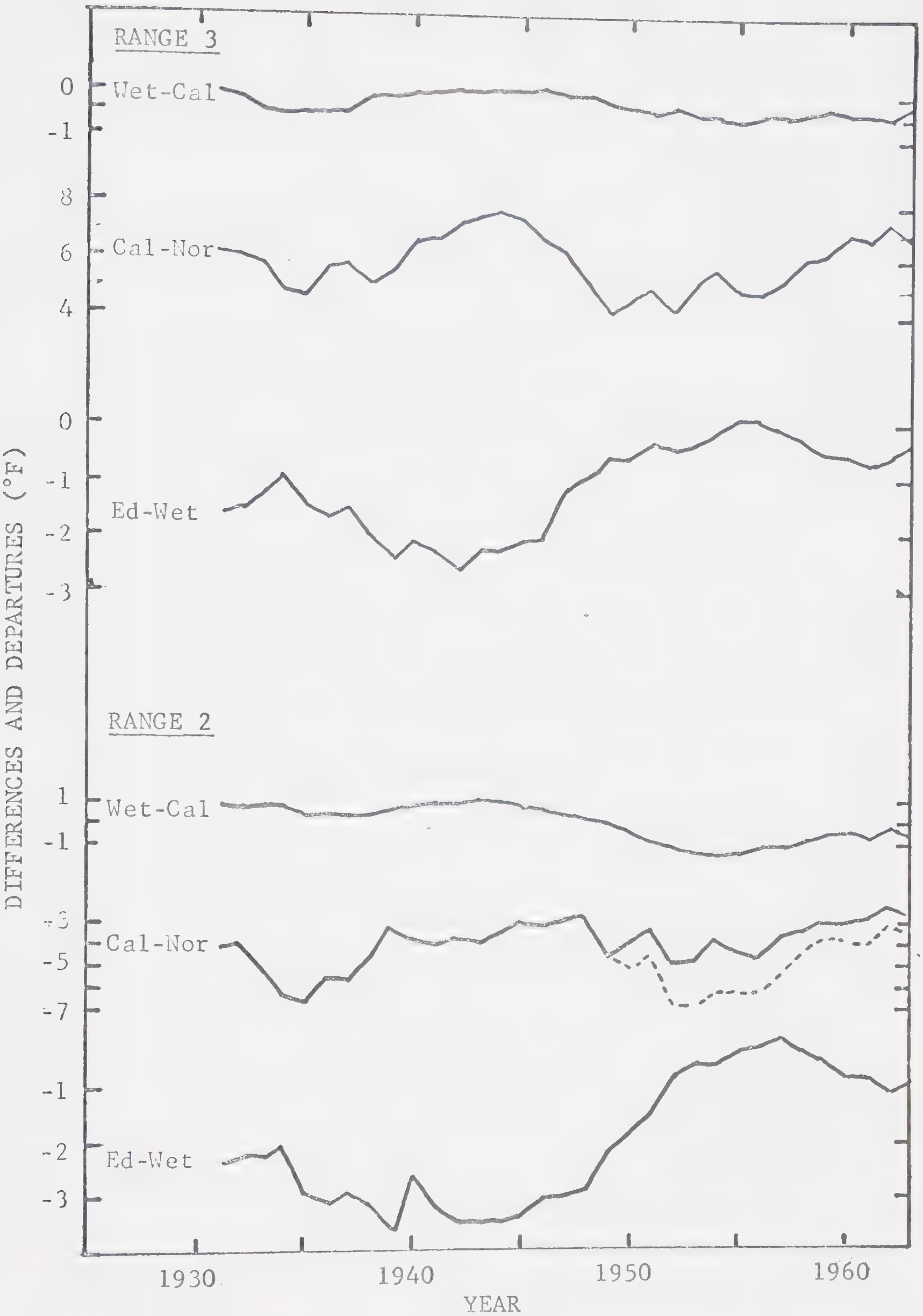


Fig. VI-2. Edmonton-Wetaskiwin (Ed-Wet) and Wetaskiwin-Calmar (Wet-Cal) maximum temperature differences for Ranges 4 to 6. Included are departures of Calmar maximum temperatures from normal (Cal-Nor). All data are five-year running means.

between departures and differences for these cold-weather values.

These relationships between maximum temperature and difference cast doubt on the degree to which the effects of urban expansion are reflected in the Edmonton-Wetaskiwin maximum temperature differences. It appears that, to some extent at least, the increase in differences in the 1940s and 1950s may have been attributable to declining temperatures, not urban expansion.

It is desirable to find some logical explanation for this relationship between departures of maximum temperature from normal and differences. One plausible explanation is as follows. Abnormally warm days are probably those with relatively intense daytime heating. This heating would produce low-level instability over the city, and hence enhance atmospheric mixing and dispersion of urban heat. That little correlation was found at temperatures below 10°F (Range 1) could be indicative of the fact that weak insolation does little to modify the strongly stable air masses typical of the winter season. This reasoning is in accord with the results discussed in Chapter V, which indicated that Edmonton-Wetaskiwin maximum temperature differences probably increased more, over the period of record, for cloudy days than for relatively clear days.

The Influence of Meteorological Factors on Minimum Temperatures

Attempts to relate the Edmonton-Wetaskiwin minimum temperature difference to sunshine, wind, temperature, percentage of days with precipitation, and departures of temperature from normal proved to be a failure. Referring back to Fig. V-1, it can be seen that three major features in the time series of yearly minimum differences beg explanation. The first is the pronounced decline in differences after 1943. The t-Test used suggested significance for this decline. An explanation is not readily

apparent, however. Perhaps a change from coal to natural gas heating in the city could have been influential. This change would have reduced pollution levels over the city and consequently reduced the city-country difference in nighttime radiational cooling.

Similarly, the decline in these differences in the early 1960s may have been significant. As stated previously, the expansion of a city past some critical level--probably about 500,000 people--generally results in only small increases in its temperature. This fact could serve to explain a plateau in the difference curve after 1960, but hardly a decline.

The third major feature is the increase in difference from the late 1940s to 1960. This increase coincided with a period of rapid expansion of the city (see Fig. III-3). It appears most reasonable to attribute this trend to the warming of Edmonton resulting from this expansion.

It is not meant to suggest from this discussion that the time series of Edmonton-Wetaskiwin minimum temperature differences were unaffected by variations in meteorological factors. However, any influence these factors had was of a nature that could not readily be resolved.

Use of Calmar Data

Calmar temperatures were used for classification purposes, in spite of their suspected defects. For example, days were classified as to range in terms of the Calmar temperature. To clarify why this was necessary, consider the case of the departures from normal previously discussed. Table VI-2 gives correlation coefficients between the Edmonton-Calmar temperature difference and the departures of both Edmonton and Calmar temperature from normal. There was a strong correlation between Edmonton-Calmar differences and Edmonton's departure from normal. However,

TABLE VI-2 - CORRELATION COEFFICIENTS[a] BETWEEN THE EDMONTON-CALMAR MINIMUM TEMPERATURE DIFFERENCE AND THE DEPARTURES OF EDMONTON (r1) AND CALMAR (r2) MINIMUM TEMPERATURES FROM NORMAL

Range	1	2	3	4	5	6
r1	.64	.53	.17	.46	.66	.84
r2	0	.07	-.27	-.04	-.05	.23

[a]The 95% significance level (t-Test) is about -.30

correlation between the same differences and Calmar's departure from normal did not appear to be particularly significant.

The example given in Table VI-2 indicates that caution must be exercised in interpreting computed correlation coefficients, even when their magnitudes are large. To explain the inconsistency in this single example would be difficult--a number of factors could have played a part. A similar effect, however, appeared repeatedly while processing the data, leading to the following probable explanation. Any attempt to correlate the temperature difference, x-y, between two stations against temperature (or some other closely related variable) at station x, produces a predisposition toward high correlation coefficients. This results from the fact that on a day for which the temperature at station x is relatively high for any reason, the x-y difference will also tend to be high. Hence, a substantial positive correlation can be produced between, say, the x-y temperature difference and the station x temperature, even though in any meaningful sense of the word, the relationship is actually random.

To eliminate this distortion of the data, it was found necessary to use Calmar values as a reference for treatment of the Edmonton-Wetaskiwin differences. The selection of Calmar temperatures for the computation of departures from normal is an example of this use. Obviously, the use

of Calmar data in any way is not ideal, in view of the apparent discrepancies in temperature at the station. Fortunately, these apparent changes at Calmar were relatively small, being about 1.5°F in the mean.

CHAPTER VII

EVALUATION OF THE EFFECTS OF URBAN EXPANSION

Method of Representation

The primary approach chosen to estimate the effects of urban expansion on temperatures in Edmonton was computation of the change in the means of Edmonton-Wetaskiwin differences. The change from the 1931-40 period to the 1956-65 period was taken. These periods were quite long; nonetheless, there was a substantial population increase from the earlier period (mean population 85,000[1]) to the later period (mean population 300,000[1]). Shortening the periods would have permitted representation of a larger change in city size. It was felt, however, that a period of 10 years was the minimum acceptable length. Shorter periods would have increased the risk of interpreting changes in the differences, resulting from other factors, to the city's expansion. This was a particularly acute problem when dealing with Edmonton-Wetaskiwin temperature differences. As previously discussed, the considerable difference in location of the two stations could have made temperature differences between them subject to variations in meteorological factors in ways unrelated to urban climate.

It is important to define precisely what this approach, involving the comparison of data between two periods, really implies. Strictly

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[1]The city's 1935 population was used to represent the mean for the 1931-40 period. For the 1956-65 period, the 1960 population was used.

speaking, there is no measure of the effects of urbanization relative to the rural setting. At best, the data provide a measure of the change in urban effects over a specific period of growth of the city. For example, a statement such as "the strong temperature dependence of the amount of Edmonton's warming in winter is probably indicative of the dominant influence of space heating on the city's temperature regime in this season" is not in the strictest sense of the word correct. Absolute accuracy would require stating that the factor was dominant in determining the change in the city's temperature regime for the specific period of expansion involved. This point is of considerable importance in that there is little information as to the nature of urban effects in the 1931-40 period. For example, it is possible that in this early period, which had a mean population of 85,000, certain urban effects may have already been established to the point where considerable further expansion of the city would have changed them very little. The comparison approach used would not resolve such factors.

Minimum Temperatures

Changes in minimum temperatures are the simplest to deal with. Referring back to Fig. V-1, it can be seen that changes in the Edmonton-Wetaskiwin differences were small prior to 1940. A relatively uniform apparent warming of Edmonton coincided with the period of the city's expansion, except for a decline in the early 1960s. There was little resolvable correlation between these differences and the year-to-year variation in meteorological factors. Consequently, temperature changes between the two 10-year periods mentioned above probably gave a reasonable measure of the effects of urban expansion. The possible influence of other factors cannot be entirely ruled out, however.

The average increase in the Edmonton-Wetaskiwin minimum temperature difference from the 1931-40 period to the 1956-65 period was found to be 2.2°F, indicating a substantial amount of warming for the city. Fig. VII-1 gives this change in the difference on a monthly basis. Included in this figure, and in Fig. VII-2, are monthly values of other factors which, as discussed in previous chapters, may affect the seasonal variation in city-country temperature differences. The values of percentage of available energy provided by natural gas consumption and automobiles were extracted from Fig. III-10. The other factors given are graphical representations of previously-tabulated data for Edmonton. The numbers of Degree Days come from Table II-8, percentage of total possible sunshine from Table II-10, and mean city wind from Table II-7. The stability data for daytime and nighttime periods represent Djurfors' (1969) summary of 1 year of data for downtown Edmonton (Table III-3). The 10-year mean stability figures for a rural location near Edmonton also come from Table III-3.

Roughly speaking, Edmonton's apparent increase in minimum temperatures was least, and approximately constant in magnitude, from April to September. All months showed an increase of at least 1°F. Outside this period of nearly constant change, warming increased rapidly to a maximum of 3.6°F in January.

Referring back to Fig. V-8, which gives the same changes as a function of temperature, instead of by month, it can be seen that Edmonton's apparent warming was strongly dependent on temperature between 0°F and -20°F. The maximum amount of warming, 5.6°F, occurred at the lowest computed temperature value, -26°F. At temperatures below -20°F, there is a suggestion that this temperature dependence diminished. Between

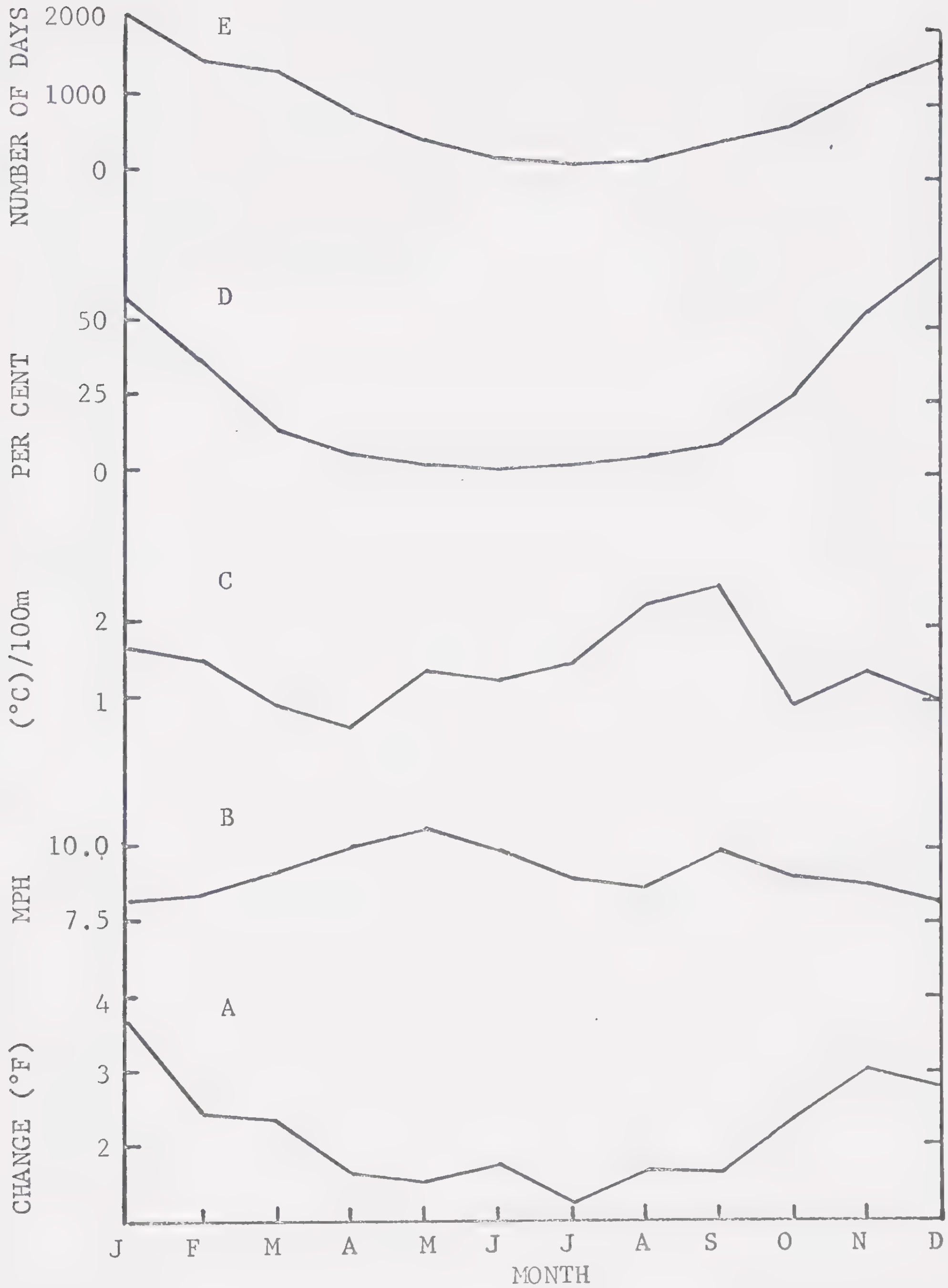

Fig. VII-1. Change in the Edmonton-Wetaskiwin minimum temperature difference (curve A) from the period 1931-40 to the period 1956-65. Other factors that may influence this difference are included.

Legend: B. Mean Edmonton (city airport) wind.
C. Mean lapse rate for 2200-0500 MST
D. Percentage of available energy provided by natural gas consumption and autos.
E. Degree Days for Edmonton

These curves are derived from previous tables (see text) which give sources.

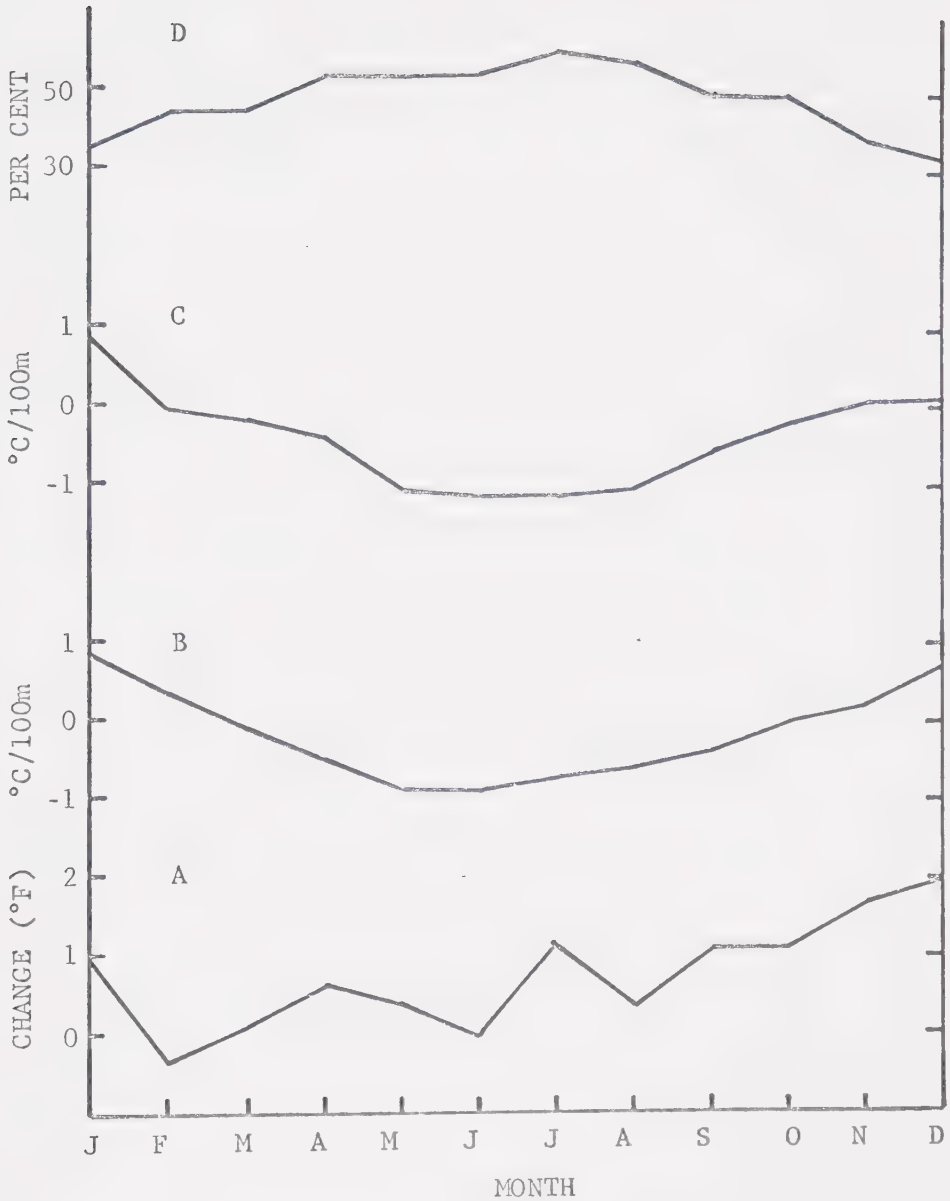

Fig. VII-2. Change in the Edmonton-Wetaskiwin maximum temperature differences from the period 1931-40 to the period 1956-65 (curve A). Other factors that may influence these differences are included.

Legend: B. Mean lapse rate from radiosonde data.
C. Mean lapse rate for 0900-1800 MST.
D. Percentage of total possible sunshine.

These curves are derived from previous tables (see text) which give sources.

10°F and 30°F, the amount of warming was nearly independent of temperature. Above the freezing point, the amount of warming decreased with increasing temperature, to zero at 56°F.

The fact that the amount of Edmonton's warming depended so strongly on temperature in cold weather suggests that energy from space heating was a major determinant. That this could be the case is not surprising. Edmonton's unusual combination of very high stability and light winds should act to produce low dispersion rates in winter months. Poor dispersion would serve to accentuate the effects on city temperature produced by the relatively large amounts of space heating required in this season. Of interest is the sudden diminishing of the rate of increase of warming at temperatures below -20°F. Referring back to Fig. III-9, it can be seen that Robertson's (1955) figures give a similar plateau in the rate of natural gas consumption in very cold weather. Although there were insufficient data to draw definite conclusions, it is worthwhile speculating as to whether the two effects are related.

The substantial increase in the frequency of fog in the city at temperatures below 0°F may have contributed to the magnitude of the city's warming in winter, both through latent heat release and long-wave radiation attenuation. It is to be noted that this substantial increase in winter temperature occurred in spite of the relatively low levels of particulate pollution over the city in winter months. This suggests attenuation of outgoing radiation by particulate pollution was not an essential factor in development of the city's minimum temperature excess in winter.

An explanation of the nature of the apparent increase in the city's minimum temperatures in warmer months is more difficult. The two major

factors in this regard are the roughly constant amount of temperature increase (1.2°F to 1.7°F) which occurred between April and September, and the small magnitude of this increase on very warm nights. For this period, the amount of heat generated in the city was small, both in comparison with winter values, and as a percentage of the total available energy. This does not mean that its influence can be ruled out completely. However, differences in city-country radiation rates, and perhaps release of stored heat, are generally considered as the major sources of city temperature excess in these warmer months.

The significance of reduced outgoing radiation rates over the city may explain why the amount of Edmonton's warming was small on very warm nights. The city-country difference in these rates is generally least on cloudy nights, when energy loss by means of long-wave radiation is relatively small. This low level of radiational cooling probably implies that these cloudy nights would also be the warmest.

Another possible explanation of this apparently small amount of warming entails the fact that the determinants of the city's temperature excess on very warm nights may have been largely established by the initial 1931-40 period, and hence as previously discussed, not appreciably affected by further urban expansion.

The second major feature of warmer months, the approximate constancy of the apparent temperature increase from April to September, is not in accord with the typical effects of urbanization in other locations, which result in a minimum city temperature excess in spring, and a maximum in fall. This typical pattern is associated with the increase in nighttime stability and decrease in wind which normally occur from spring to early fall.

Referring to Fig. VII-1, it can be seen that these trends in wind and nighttime stability are generally adhered to in Edmonton. In addition, Table III-4 indicates a pronounced decline from spring to fall in the frequency of winds from the northeast and from the north. These directions give the shortest urban trajectories to the air prior to its arrival at the airport observing site.

Apparently, therefore, dispersion rates over Edmonton decline from spring to fall, and coincidently, there is an average increase in the length of urban trajectory of the air prior to its arrival at the airport. Why therefore, was there no significant increase in the amount of warming of minimum temperatures over this period? Assuming that the data truly reflect the effects of urban expansion, there is no obvious answer to this question. The simplest explanation would be that, for this particular period of expansion of the city, the factors causing the increased urban temperature excess were relatively unaffected by the magnitude of the seasonal trend in dispersion rates. Unfortunately, this magnitude appears to be substantial. One difficulty arises at this point, however. Wind and stability data represent mean conditions for all days of the month. As discussed in Chapter V, for warmer weather, only a limited number of days underwent warming. It is possible that these days corresponded to days for which dispersion rates were below some critical value. This being the case, changes in the monthly means of wind and stability (or other factors such as pollution) may not give an adequate representation of the change in the number of days below the critical level.

At any rate, the apparent increase in Edmonton minimum temperatures in warmer months is most likely attributable primarily to reduced long-

wave radiation rates over the city. Nighttime release of stored heat could also have been a factor, although, in comparison with a highly built-up downtown area, the general airport area where temperatures were recorded did not appear to be particularly favourable for this effect.

Maximum Temperatures

As previously discussed, the Edmonton-Wetaskiwin maximum temperature differences appeared to be dependent to some extent on the year-to-year variation of maximum temperatures. Consequently, caution must be used in interpreting the results. By taking changes in the difference between two 10-year periods, the effects of this dependence can be reduced. Unfortunately there was, however, through the period of study, a gradual decline in maximum values. This decline is illustrated in Table VII-1. Since this relationship between differences and temperatures

TABLE VII-1 - MEAN CHANGE (C) IN WETASKIWIN MAXIMUM TEMPERATURES FROM 1930-41 TO 1956-65

Month	J	F	M	A	M	J	J	A	S	O	N	D	Annual
C (°F)	-3.0	1.9	-2.3	-0.6	-1.2	0.7	-1.0	-1.0	-2.5	-1.1	-0.8	-1.7	-1.1

appeared to be inverse in nature, it is not impossible that at least some of the increase in Edmonton-Wetaskiwin maximum temperature differences could have been attributable to a temperature decline, instead of to urban influences. Comparison of the changes in temperature given in Table VII-1 with the changes in difference given in Fig. VII-2 does not, however, indicate any simple relationship between the two factors. For example, the general increase in the change in the differences from June to December did not correspond to any discernable trend in the change in the magnitudes of maximum temperatures.

At best then, it is to be hoped that the changes in the maximum temperature differences between the 1931-40 period and the 1956-65 period were not seriously distorted by the typically small decline in mean maximum temperatures represented in Table VII-1. Assuming this to be the case, the increase in Edmonton maximum temperatures between the two periods was, in the mean, 0.7°F. The seasonal trend in the amount of apparent warming, from near zero in spring to a maximum of 1.9°F in December, was in accord with the coincident trends of increasing daytime stability and decreasing wind, as indicated in Fig. VII-2. It is difficult to explain, however, why this apparent warming should have decreased so sharply from the December high to near zero in February.

What appeared to be a strong influence of the production of heat in the city on changes in minimum temperatures was not evident for maximum values. The fact that the maximum amount of apparent warming of these latter values occurred in early winter is probably in part attributable to high levels of space heating. As previously discussed, for minimum temperatures the influence of artificially produced heat was probably reflected in the strong temperature dependence of the amount of warming at temperatures below 10°F. Reference to Fig. V-4 indicates this dependence was lacking in the case of maximum values. The problem is confused, however, by the sharp drop in apparent warming in the latter part of the winter.

Fig. V-4 indicates that Edmonton's apparent warming for maximum temperatures was nearly independent of temperature between 10°F and 50°F. Too much significance should not be attached to this fact however, because to a considerable extent it probably reflects a balance between low spring values and relatively higher fall values.

Above 50°F the magnitude of the increase in temperature appeared to decrease to about zero at 70°F and above. Very warm days generally represent days with intense solar heating. Sufficient instability (and hence dispersion of urban influences) could result from this heating to nearly eliminate city-country temperature differences.

Mean Temperatures

The seasonal warming trend indicated by the change in the Edmonton-Wetaskiwin temperature differences for mean temperatures is indicated in Fig. VII-3. Edmonton's apparent warming in this case was relatively constant at about 1°F from February to August. November, December, and January showed substantially larger amounts of warming than other months.

General Remarks

Table VII-2 summarizes the apparent warming of Edmonton for maximum, minimum, and mean temperatures, as computed from changes in differences between the two 10-year periods. The net increase of 0.8°C is comparable to the average figures for other cities given in Table II-1. It is about 50 per cent higher than the mean figure given by Landsberg for cities of 100,000 to 500,000 people (Table II-2). It must be borne in mind, however, that values of city temperature excess, such as those given in Table II-1, were computed from differences in temperature between rural and urban sites. Consequently, the values of city temperature excess given in Table II-1 are representative of a change in population from near zero at the rural sites, to over 500,000 (in most cases) in the city. In comparison, the computed increase in temperature at Edmonton is representative of an increase in population of only 215,000 (from a mean population of 85,000 in the 1931-40 period to a mean population of 300,000 in the 1956-65 period). The fact that this increase of 215,000 in city population could have produced an increase in temperature com-

TABLE VII-2 - AVERAGE VALUES OF EDMONTON-WETASKIWIN TEMPERATURE DIFFERENCES FOR THE PERIODS 1931-40 AND 1956-65

Temperature (°F)	Max.	Min.	Mean
1931-40	-1.2	0.1	-0.5
1956-65	-0.5	2.3	0.9
change	0.7(0.4°C)	2.2(1.2°C)	1.4(0.8°C)

parable to the city-country differences given for other large cities can probably in part be explained in terms of the combination of low dispersion rates and the large magnitude of space heating which occurs in colder months.

In view of the fact that most of the city temperature excess generally develops before the city's population grows past the half-million mark, it is possible that the period of study corresponded to the critical growth period as far as temperature increase was concerned. It is of interest to speculate as to whether the interruption in the warming trend in Edmonton around 1960 was, at least to some extent, indicative of the onset of a period in which temperature increase as a result of urban expansion became less.

A final word is necessary regarding the representativeness of the data from the city airport, which is well away from the city center. Daniels' (1965) isotherm charts for the city (Fig. III-13 to Fig. III-16) indicate that the amount of city temperature excess recorded at the airport was about one half the maximum, which generally occurred near the city center. In view of this fact, it is tempting to suggest that the increase in temperature in the downtown area would have been considerably greater than at the airport. In reality, it is not impossible that

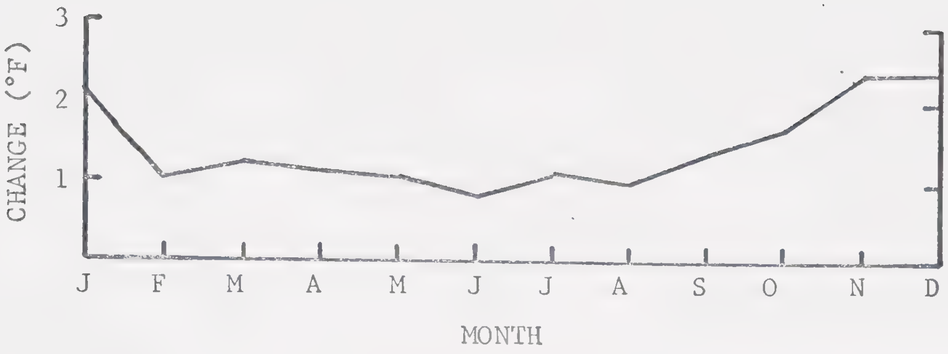

Fig. VII-3. Change in the Edmonton-Wetaskiwin mean temperature differences from the period 1931-40 to the period 1956-65.

the reverse may have been true. In the 1931-40 period, downtown Edmonton was already surrounded by a substantial urban area. It was after 1940 that urban development occurred around much of the airport. It is not impossible that the net effect of this development pattern could have been to increase airport temperatures more than those in the downtown area. In view of the lack of data in this regard, it appears unwise to attempt to draw firm conclusions about temperature changes in other parts of the city from airport data.

CHAPTER VIII

SUMMARY

Validity of Results

There were two basic difficulties involved in the use of time series of Edmonton-Wetaskiwin temperature differences to gauge the effects of urban expansion on the city's temperature. First, because the city-country temperature difference varies greatly with changing weather patterns, there was a risk that year-to-year fluctuations in such meteorological factors as temperature could have influenced the computed differences. Second, the substantial differences in latitude and elevation between the two stations created the risk that variations in meteorological parameters could have influenced the Edmonton-Wetaskiwin differences in ways unrelated to urban climate.

A detailed analysis of the data failed to indicate that these two difficulties were important in the case of minimum temperatures, when data were in the form of time series of, say, monthly or yearly means. There was no evidence, therefore, that the general upward trend in the minimum temperature differences was related to factors other than urban expansion.

The situation for maximum temperature was more difficult. Apparently, there was some form of inverse relationship between differences and temperature. This influence could be reduced somewhat by taking mean changes in the differences between two 10-year periods. Unfortunately there was, however, a decline in mean maximum temperature from the earlier to the

later period. Hence, it is not impossible that some of the indicated increase in Edmonton-Wetaskiwin maximum temperature differences could have resulted from this decline, instead of from urban expansion.

Minimum Temperatures

Assuming a reasonable degree of accuracy in the use of Edmonton-Wetaskiwin temperature differences as a measure of urban influence on the city's minimum temperatures, it can be stated that the change in city size from a population of 85,000 to one of 300,000 produced a substantial 2.2°F increase in these temperatures. In cold weather---minimum temperatures below 10°F--the amount of warming was greatest, and strongly temperature dependent, increasing with decreasing temperatures to a maximum of 5.6°F at -26°F. The explanation of this behaviour probably rests with the combination of low dispersion rates and high levels of space heating in winter months. The fact that these substantial increases occurred in spite of low winter levels of air pollution would suggest that attenuation of outgoing radiation by this pollution was not an essential factor in the development of the city's minimum temperature excess in winter.

The somewhat smaller amounts of warming indicated for summer months were most likely caused primarily by reduced long-wave radiation rates in the city. Some degree of support for this is given by the fact that the amount of warming declined to zero on very warm nights. These nights were probably those with extensive cloud cover and consequently little difference in city-country radiation rates. Additionally, for all temperature ranges, warming was least on days with precipitation, which were presumably the days with most cloud.

No simple explanation could be found for the near constancy of the amount of warming from April to September, in spite of increasing stability and decreasing wind through the period. Perhaps the available values

for these latter two factors were not sufficiently detailed.

At minimum temperatures below -15°F, it appeared that all days underwent some degree of warming. For warmer temperatures, there was a set of days upon which urban expansion had little effect. These were days upon which Edmonton was, in the early period, warmest with respect to Wetaskiwin. Relatively less stable conditions may have been associated with these days. If this were the case, relatively high atmospheric dispersion rates would have tended to minimize city-country temperature differences. Additionally, the Edmonton-Wetaskiwin maximum temperature difference would have tended to be higher on these less-stable days because of the higher elevation of the latter station.

Maximum Temperatures

For the reasons previously discussed, caution must be exercised in interpreting the apparent warming of maximum temperatures, as indicated by the Edmonton-Wetaskiwin differences. Nonetheless, the seasonal trend from little warming in spring to a maximum in December was in accord with both typical results from other locations, and the local seasonal variation in wind and daytime stability. The abrupt decline in the amount of warming in the latter part of the winter is not easily explained, however. Perhaps the influence of changes in mean maximum temperature played a part.

At any rate, the indicated amount of warming of maximum temperatures was, in the mean, 0.7°F, or only about one third the amount for minimum values. This is to be expected in view of the fact that city-country difference is generally small in the early afternoon when maximum temperatures are normally recorded. The largest monthly increase was 2.0°F in December. Although this maximum amount of warming occurred in a period

when the amount of space heating was large, no clear indication of the role of this heat source could be found.

There was a number of days which appeared to be unaffected by urban expansion in the case of maximum values. As in the case of minimum temperatures, these were days in which Edmonton, in the earlier period, was warmest with respect to Wetaskiwin. This effect could be seen in all temperature ranges.

In contrast to minimum values, maximum temperatures showed greatest apparent warming with time in the city on days with precipitation. This was probably indicative of the fact that city-country difference in the afternoon was greatest on cloudier days, perhaps because of increased stability.

General Remarks

The mean increase of 1.4°F in Edmonton's temperature was substantial in view of the relatively modest[1] gain in population between the two comparison periods used. The combination of low atmospheric dispersion rates and high levels of space heating was probably partly responsible for the size of this increase. Additionally, the period studied may have been the critical period in which much of the city's temperature excess developed. The interruption in the upward trend in differences around 1960 may have been evidence of transition to a period in which further temperature gains resulting from urban expansion were small.

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[1]"Relatively modest" in comparison with the population "increase" represented by comparison of temperatures at a rural site and in a large city. This matter is discussed in Chapter VII.

It must be remembered that the data presented are representative of the airport observing site, roughly 2 miles from the city's center. Extreme caution must be used in attempting to apply these results to other areas of the city.

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